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AUDITORIUM ACOUSTICS AND REVERBERATION

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Within a closed space the sound which reaches the ear after one or more reflections at the walls has an important influence on the quality of music and the intelligibility of the spoken word. In this article this phenomenon of reflection, called reverberation, is studied by means of measurements and calculations. This study leads finally to several simple conditions which must be fulfilled if an auditorium is to have satisfactory acoustics.

Introduction

Speech and music both consist of sound vibrations which must reach the ear in a definite succession in order to be intelligible. If the source of the sound and the hearer are both in the open, the succession of vibrations is the same as that in which the sound waves were produced. In a closed space, however, it sometimes happens that vibrations which were produced earlier, after several reflections at the walls, reach the ear simultaneously with those which were sent out later. The order of the sound impressions is therefore disturbed to some extent. It is easy to understand that speech can in this way become less intelligible and music can be run together in such a way that the notes no longer sound distinct. If the source of sound is suddenly silenced, the sound of the reflected waves is still heard for a short time. This phenomenon, reverberation, is of the greatest importance in the acoustics of an auditorium, because of its influence on the intelligibility of speech and quality of music.

Why is it not possible to render the reverberation so slight that no reflection of sound takes place? This would seem to be an excellent plan in the case of speech.

In the first place it is not so easy to achieve this; moreover, if it were done, the sound from a source of a given power would be much weaker than otherwise, as can be ascertained by comparing the music of a violin in a hall with the same music out of doors. Finally there are psychological and aesthetic reasons why we desire a certain amount of reverberation in music. The rolling tones of the organ in the vaulted roof of a Gothic cathedral have a peculiar beauty.

We are thus compelled to look for a compromise between two effects:

a) when the reverberation time is long, the speech is loud but non-intelligible;

b) when the reverberation time is short, the sound is not sufficiently reinforced by reflections, nor is it uniformly distributed over the space.

It has been found that the optimum reverberation time is about two seconds for large halls, while for small halls, where the sound does not need so much reinforcement, one second is the best time.

Sabine's experiments

In the middle of the last century the importance of reverberation to the acoustics of an auditorium was already recognized. It was also known that reverberation was dependent on the volume and shape of the hall, but the nature of this dependence was not known. An exact copy of a hall with good acoustics, but on a larger or smaller scale, was sometimes found to give unexpectedly bad results. Moreover, such knowledge as there was had not penetrated sufficiently well into the sphere of architecture. Architects believed in a certain aesthetic relation between the dimensions of a hall, which was supposed to produce good acoustics. It was not until 1900 that a quantitative insight was obtained into the phenomenon of reverberation through the experiments of the American physicist Sabine, and it was still about twentyfive years before the principles so discovered were applied in the actual building.

Sabine was commissioned to make improvements on an auditorium with bad acoustics by shortening the reverberation time. In order to be able to do this, he wanted to find a relation between the various quantities which affect the reverberation time, namely, the volume of the space, the area and the absorption of the walls. To do this, he measured the reverberation time of various halls at Harvard University with an organ pipe and a chronograph. As reverberation time he took the time elapsing between the moment of shutting off of the source of sound after a steady sound intensity has been reached and the moment when the tone of the organ pipe became inaudible. He then found that reverberation is directly proportional to the volume of the hall, and that in general the curve of the walls and their relative positions have no noticeable effect on reverberation.

By the introduction of seat cushions from a theatre auditorium, he was able gradually to reduce the reverberation time of a given space from 5.35 sec to 1.14 sec. In this way he obtained a relation between the reverberation time and the number of metres of cushions introduced. This criterion was later changed into square metres of cushions, and still later into square metres of open window, after he had found out on a quiet night that the absorption of an open window was proportional to the size of the opening, and that his cushions absorbed 80 per cent of what the same area of open window absorbed. It is obvious that all the sound incident upon an opening passes through it. The number 0.8 was called the absorption coefficient by Sabine. This number, which is less than one, indicated the fraction of 1 sq metre of open window which has the same absorption as 1 sq metre of the material under consideration. In other words, this number is the ratio between absorbed and incident sound. Sabine was now able, by means of measurements in halls with different wall coverings, to determine the corresponding absorption coefficients. Account had also to be taken of the absorption of sound by the audience, which corresponds to about 0.5 sq m of open window per person.

By combining all these measurements experimentally, he obtained the very well known relation:

$$T = 0.16 \frac{V}{\Sigma a_i S_i}, \quad \cdot \cdot \cdot \cdot \cdot \quad (1)$$

in which T is the time elapsing between the shutting off of the source of sound and the fall of the sound intensity to inaudibility; V is the volume of the space, S_i the area of a part of the wall and a_i the corresponding absorption coefficient. $\Sigma a_i S_i$ is then taken over the total surface of the walls and other absorbers (such as the audience), each with its own absorption coefficient.

Considering the complexity of the phenomenon of reverberation, Sabine's formula is extraordinarily simple. It is striking that reverberation is independent of the shape of the space and of the nature of the distribution of the absorbing surfaces over the walls, and of the position of the source of sound and of the observer. It is this very simplicity which makes Sabine's formula so useful for calculating the reverberation time of a hall from its plans and from the known absorption coefficients of the material of the walls, or for the determination of absorption coefficients from reverberation measurements such as Sabine himself carried out in the above-described experiments with chair cushions.

From equation (1) it is immediately clear that when there is no absorption ($a = 0$) the reverberation time is infinite, a fact which is clear enough even without a formula.

If the whole wall surface consisted of material which was completely absorbent, or equivalent to "open window" no reflections would take place and the reverberation time would have to be zero. This result is not confirmed by equation (1); $\Sigma a_i S_i$ becomes equal to the area of the surface of the wall and not infinitely great, so that T cannot become arbitrarily small. From this it may be seen that Sabine's formula is subject to limitations.

Later in this article we shall attempt to derive Sabine's formula from the elements of the theory of sound. It will then become clear that equation (1) holds accurately only when the absorption of sound is so small that each wave is subjected to a large number of reflections before it dies out. When this is not the case, reverberation is dependent on the shape of the hall and on the distribution of the absorbing materials. It is, however, possible to improve upon Sabine's formula in such a way that it remains valid for an approximately cubical shape of hall and a uniform distribution of the absorbing material even with strongly absorbing walls.

Measurements of reverberation

Before we consider the reverberation phenomenon theoretically, we shall first give some details about the measurement of reverberation time.

Sabine carried out his measurements with an organ pipe and a chronograph. Such subjective measurements, which are sometimes still done, require a great deal of practice. Many measurements must be carried out, and their average taken, in order to obtain anywhere near a reliable result.

The accuracy of the measurements can be much improved if there is available a gramophone, an amplifier with loudspeaker, a potentiometer calibrated in decibels and an electric clock. A record with a continuous so-called warble tone is put on the gramophone. This tone is one whose frequency varies rapidly over a short range. It is used to prevent the occurrence of standing vibrations in the measuring space, which would be certain to occur if a single frequency were used, and which would adversely effect the measurement.

The circuit can be arranged in such a way, that the clock only runs when the loud-speaker is shut off. The potentiometer is set 60 db above the limit of audibility which was determined previously and the loudspeaker is switched on. One now waits until the sound intensity has become steady, the switch is then reversed so that the loudspeaker is silenced and the clock begins to run. When the limit of audibility is reached, the switch is again reversed, the loudspeaker begins again, and the clock stops. This can be repeated as often as desired, and the clock adds up the reverberation times measured. It is only necessary to divide by the number of measurements to obtain the average reverberation time. With some practice an accuracy of 5 to 10 per cent can be attained by this method.

Instead of setting the potentiometer at 60 db it may also be set at 50, 40, etc. A linear relation must then be found between these numbers and the time which elapses until the sound is inaudible. The slope of the straight line which most nearly connects these points gives the reverberation time.

For short reverberation times these subjective methods give poor results. In order to exclude the human element, an entirely automatic apparatus has been constructed for measuring reverberation time. Wide use is being made nowadays of recording meters with a logarithmic scale. They have the advantage of recording not only the reverberation time but the whole course of the reverberation, which makes it possible to determine the reverberation time with more judgment. Moreover, certain conclusions may be drawn from the course of the reverberation about the acoustic properties of the space measured. This may be illustrated by the three curves recorded with a logarithmic voltmeter. The first curve (*fig. 1*) is a normal reverberation curve, which, aside from numerous small fluctuations, corresponds well with a straight line. The reverberation time is 1.75 sec. The second curve (*fig. 2*) was recorded after damping material was introduced into the room on the floor and along the walls, but only extending half way to the ceiling. We can no longer speak of a single reverberation time. The curve consists of two overlapping parts. The first has a reverberation time of 0.6 sec, the second of 1.75 sec; the latter corresponds to the upper half of the room. The reverberation time, which according to equation (1) is determined by the ratio V/A for equal absorption coefficient, is the same as in fig. 1 because V/A has the same value for this half as in the first recording for the whole room. The short reverberation time is that of the damped half. It may

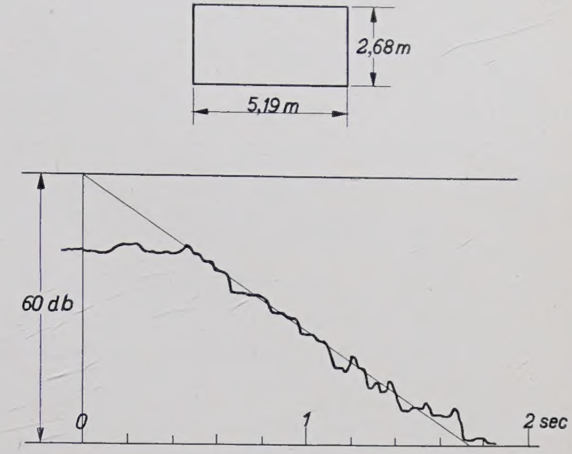

Fig. 1. Recording of the sound intensity in a room as a function of the time. The reverberation time is 0.75 sec. Above, a vertical cross section of the room.

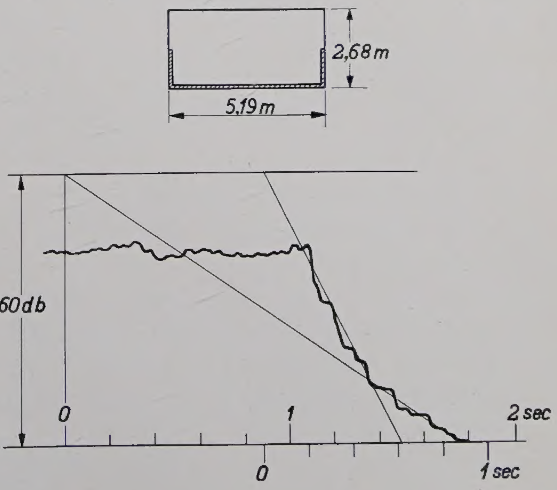

Fig. 2. Recording of the sound intensity in the same room while the lower half is covered with absorbing material, as indicated in the cross section. In the recorded curve two reverberation times may now be seen belonging to the two halves of the room.

therefore be seen from this record that when the damping material is so unequally distributed as in this case, reverberation does not follow a simple exponential course, but consists of two connected exponential branches. In the figures these are straight lines, since the intensity scale is exponential.

In the third recording the door of the room was opened wide and care was taken that the sound passing through the door did not immediately re-enter the room. This was done by means of a screen placed diagonally outside the door. The reverberation time of the lower portion of the room has now become shorter, namely 0.2 sec, because the absorption of the open door is now added to that of the material introduced; the other reverberation time has become somewhat longer because the sound which enters the corridor, after it has passed from one end to the other of the corridor, re-enters the room and again passes out through the door. This occurs several times until the sound has died out. The transition between the two parts of the reverberation curve is much sharper here. The reverberation time of the corridor is also expressed in this curve, and is somewhat longer than that of the room. The recorded reverberation times are obtained by picking up the sound with a microphone, whose alternating voltage, after amplification, is traced on the above-mentioned recording meter on a film 35 mm wide, which is made especially for mechanical tracing. In these recordings the speed of the film was 25 mm per sec, and the tracing speed 600 db per sec, that is, the maximum speed at which the needle moves is such that it would be able to cover 30 cm in the direction of the intensity scale in one second. Since on this scale 60 db correspond to 3 cm, we call this 600 db. The principle of this recording arrangement is based in general on an amplifier with potentiometer, which is operated mechanically in such a way that the output voltage of the amplifier remains constant. Thus, if the input voltage falls or rises, the potentiometer is mechanically adjusted so that the output voltage always remains the same. The mechanical control arrangement at the same time operates the tracing needle and provides for sufficient force and speed for tracing.

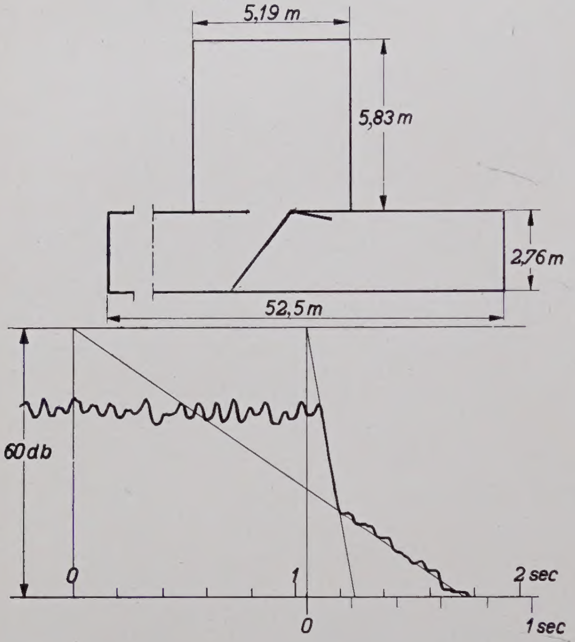

Fig. 3. Recording of the sound intensity in the same room with the door to the corridor open, according to the plan drawn above. In the recorded curve may be seen the short reverberation time of the room itself as well as the long reverberation time of the corridor. The impression is actually given that the last reverberation enters the room from the corridor.

Photographic copies of these records can be made in unlimited mumbers.

A few years ago an important new method was developed for measuring the reverberation in concert halls filled with people, without its being necessary to take other measures than those which are necessary for broadcasting such music over the radio. In the score of a piece of music to be broadcasted, portions can be picked out where the music suddenly stops at a sufficiently high level of sound and is followed by a sufficiently long rest. A radio set may now be connected in front of the recording apparatus and the recording begun just before beginning of the rest. During the rest the dying out of the sound is recorded and thus the average reverberation time under the conditions under which the hall is normally used.

If it is desired to measure the reverberation time as a function of the frequency in this way, the output voltage of the radio set must be filtered, so that only a narrow frequency band enters the recording apparatus. By using successive octave filters (filters which pass only one octave) the whole course of the reverberation time as a function of the frequency can be recorded. It is then found that the reverberation time is practically never entirely independent of the frequency, and usually becomes greater towards the low frequencies.

Theoretical treatment of reverberation

Considering the importance of Sabine's formula, it is not surprising that there have been repeated attempts to derive this formula theoretically. The value of these attempts lies in the fact that each time a better insight is obtained into the limits of the validity of Sabine's law. We shall give here a simple derivation of Sabine's law for an idealized case.

Let us assume that we are concerned with a space enclosed by hard walls which reflect sound totally. Let us now allow a source of sound to act for a short time and then stop. After some time *it is probable that the space is uniformly filled with sound due to repeated reflections,* at least if the shape of the space is not of such a regular form that the sound continues to travel in certain paths.

In order to understand this we shall find out with the help of *fig. 4,* how the filling of the space with sound takes place. The heavy lines represent a rectangular room without absorption, with perfectly reflecting walls, and a source of sound P. We wish to know the intensity of sound at an arbitrary point M of the room between the moments t and $t + \Delta t$. The direct sound comes from P; the sound once or oftener reflected comes from the mirror images of P, which are indicated in the figure by small dots. If, for example, at the moment $t = 0$ a sound impulse (a pistol shot) left P, then between t and $t + \Delta t$, the impulses of the virtual sources of sound, which lie in the spherical shell between ct and $c\,(t + \Delta t)$ are heard at M. The volume of the shell between the spheres ct and $c\,(t + \Delta t)$ increases proportionally with the square of the time, and this holds also for the average number of virtual sources of sound in the shell. As may be seen from the figure, the virtual sources of sound form a regular pattern in space, so that they will on the average be distributed uniformly over the shell. There are naturally always accidental fluctuations about the most probable value, not only in the number of virtual sources of sound, but also in their distribution over the sphere. These fluctuations, however, become continually smaller as the number becomes greater. The average number of virtual sources of sound, and therefore the average intensity, is independent of the position of M in the space, and the sound waves travel on the average with equal intensity in all directions.

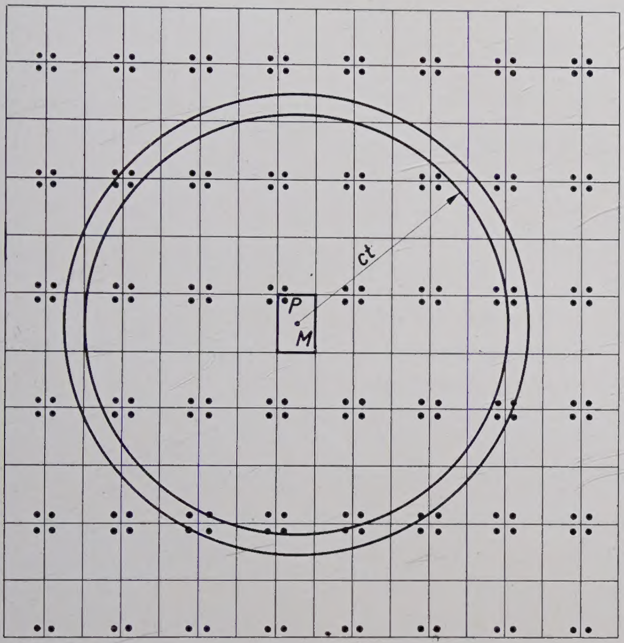

Fig. 4. Reflections of a sound impulse starting from P in a room with totally reflecting walls. Between t and $t + \Delta t$ at M the sound from all the virtual sound curves lying between the two circles is heard. In this way the sound is always evenly distributed.

The space is now filled with an energy VE_0, when V is the volume and E_0 the uniform energy per cc. Let us now make a hole in the wall with an opening A. All the energy will finally pass out through this opening. The energy passing through 1 sq.cm of the opening per second is $cE/4$ (see small print for proof). The energy incident on the whole opening is $cEA/4$. This is therefore equal to the decrease in total energy per second, since all the energy falling upon the opening is lost. Therefore

$$\frac{\mathrm{d}\,(VE)}{\mathrm{d}t} = -\frac{cEA}{4} \quad \ldots\ldots \quad (2)$$

The solution of this is

$$E = E_0\, e^{-\frac{cA}{4V}t} = E_0\, 10^{-0.434\,\frac{cA}{4V}t}\,.$$

Now in order to find a definite reverberation time T we assume that the reverberation becomes inaudible when the energy density of the sound has become a factor f smaller. Therefore

$$\left.\begin{array}{l} 10^{0.434\,\frac{cA}{4V}\cdot T} = f\,, \\ T = \dfrac{4V}{cA}\,\dfrac{\lg f}{0.434} = 0.0268\,\dfrac{V}{A}\,\lg f, \\ \text{while Sabine had found} \\ T = 0.16\,\dfrac{V}{A} \end{array}\right\} \quad \ldots \quad (3)$$

It may thus be seen that Sabine's experiments agree with the assumption that the reverberation becomes inaudible when the density of the energy has decreased by a certain factor. From the two equations (3) it follows approximately that

$$\lg f = 6; \qquad f = 1.000\,000.$$

The density of the energy therefore decreases to one millionth of its original value before it is inaudible, thus it decreases by 60 decibels. The sound pressure varies proportionately to the square root of the density of the energy, and therefore decreases during the reverberation to one thousandth of its original value.

The reverberation is of course heard somewhat longer by one observer than by another. For physical measurements, however, the time corresponding to a decrease in intensity of 60 db is generally taken as the reverberation time.

Derivation of the formula $cE/4$ for the energy flux through the unit of area.

In a volume dV (*fig. 5*) there is an amount of energy EdV. The portion of this which falls upon the surface dS lies within the solid angle $d\Omega$ within which the surface dS is seen from dV. This solid angle is given by

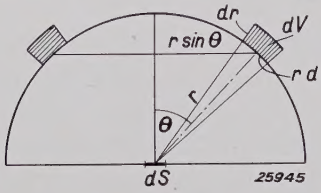

Fig. 5. Derivation of the energy flux through the unit area.

$$d\Omega = \frac{\cos\Theta \, dS}{r^2},$$

when r is the distance between dV and dS, and Θ the angle between the normal to dS and the line joining dV and dS. We begin with the assumption that the energy flows from dV uniformly in all directions. Of the energy EdV, which is in dV at a given moment, the amount $EdV \frac{\cos\Theta \, dS}{4\pi r^2}$ will fall on the surface dS.

All the volume elements from which a line to dS makes an angle Θ with the normal to dS, now lie in a torus whose diameter is $rd\Theta \cdot dr$, and the large circle has a circumference of $2\pi r \sin\Theta$. Therefore, $dV = 2\pi r \sin\Theta \cdot rd\Theta \cdot dr$. The energy from dV which falls on dS is thus

$$E \cdot \frac{\cos\Theta \, dS}{4\pi r^2} \cdot 2\pi r^2 \sin\Theta \, d\Theta \, dr = \frac{E}{2} \cdot \sin\Theta \cos\Theta \, d\Theta \, dr \, dS.$$

The total energy received by dS in the time dt comes from a hemisphere with radius cdt, when c is the velocity of sound

$$E_{\text{tot}} = \frac{E}{2} \, dS \int_0^{cdt} dr \int_0^{\pi/2} \sin\Theta \cos\Theta \, d\Theta = \frac{Ec}{4} \cdot dS \, dt.$$

An amount of energy equal to $\frac{Ec}{4}$ thus falls upon 1 sq cm per second.

Sound amplification by reverberation

As already mentioned, a certain degree of reverberation is desirable because the intensity of the sound with a given energy of the source is thereby increased. In order to investigate this amplification we make use of the total absorbed energy calculated in the foregoing

$$\frac{cEA}{4} = \frac{cE}{4} \Sigma a_i S_i \cdot$$

This energy in the state of equilibrium is equal to the energy P radiated from the source of sound. The density of the energy in the space, which determines the intensity of sound, is, therefore, at equilibrium

$$E = \frac{4P}{c \Sigma a_i S_i} \cdot$$

Now, according to Sabine's formula

$$\frac{1}{\Sigma a_i S_i} = \frac{T}{0.16 V},$$

so that the density of energy

$$E = \frac{4}{0.16\,c} \cdot \frac{P}{V} T = 0.072 \frac{P}{V} T \cdot$$

The intensity of sound is therefore proportional to the energy per unit volume and to the time of reverberation. For very short reverberation times this formula is no more valid than Sabine's formula; the sound intensity does not become zero, but passes over to the intensity of the direct sound.

Deviations from Sabine's formula.

In the foregoing derivation the essential assumption was that the space was uniformly filled with sound. Actually this means that the absorption must be so small that a large number of reflections are necessary to cause the sound to die out. When this is not so, for example, when all the sound is absorbed so that no reflection at all takes place, deviations from Sabine's formula occur. This was shown in the discussion of Sabine's experiments.

In order to set up a refined theory of absorption we shall follow a ray of sound along its path. This ray of sound will cover paths of different lengths, l_1, l_2 --- l_n, between each two successive reflections at a wall, and sound will be absorbed at each point of reflection. For ease in calculation we shall use a mean value of l, the so-called mean free path of the sound. The calculation can best be followed by means of an example. Suppose we have a room with a free path of 20 metres and an absorption coefficient on all walls of 0.50. The sound covers a distance of 340 m per second, and $340/20 = 17$ reflections take place. At each reflection 0.50 of the original sound intensity remains, and therefore after n reflections 0.50^n. To become inaudible this intensity must fall to 0.000 001. From this we can determine n: $0.50^n = 10^{-6}$, $n = 20$. The total number of reflections is thus 20, and there are 17 reflections per sec. The reverberation time is therefore $20/17 = 1.18$ sec.

The mean free path l used in the above theory is dependent in the first place on the ratio V/A of the volume of the hall to the reflecting surface. If the number of reflections is sufficiently great the free path, independent of the shape of the room, becomes

$$l = \frac{4V}{A} \text{ (see small print for proof)} \quad \cdot \cdot \quad (4)$$

Therefore in the above example $4V/A = 20$ metres. Now that this ratio is known, we can also apply Sabine's formula to the example in question and we find

$$T = 0.16 \frac{V}{\Sigma a_i S_i} = 0.16 \frac{V}{0.5\ A} = 0.08 \cdot \frac{4V}{A} =$$
$$= 0.08 \cdot 20 = 1.6 \text{ sec.}$$

This differs considerably from the value of 1.18 sec calculated above.

It is therefore clear that the treatment given above differs from the calculation according to Sabine's formula. If we now repeat the expression in general terms, we must obtain a different formula for the reverberation. The reverberation time is now the total number of reflections N divided by the number of reflections per sec (n), and the latter number is the velocity of sound divided by the mean free path, thus

$$n = \frac{c}{4V/A} = \frac{cA}{4V}.$$

The total number of reflections may be found from $(1 - \alpha)^N = 10^{-6}$, where α is the absorption coefficient, thus:

$$N = \frac{-6}{\lg (1 - \alpha)} = \frac{-6 \ln 10}{\ln (1 - \alpha)}.$$

Combining we obtain

$$T = \frac{N}{n} = \frac{N \cdot 4V}{cA} = \frac{24 \ln 10}{c} \cdot \frac{V}{-A \ln (1 - \alpha)} =$$
$$= 0.16 \frac{V}{-A \ln (1 - \alpha)} \quad \cdot \cdot \cdot \cdot \quad (5)$$

For small values of α this formula passes over into the original Sabine formula, namely

$$T = 0.16 \frac{V}{\alpha A}.$$

In this derivation we have taken a uniform value of the absorption coefficient. It is clear that if this coefficient varies slightly over the walls, instead of $-A \ln (1 - \alpha)$ we must take in the denominator $\Sigma - S_i \ln (1 - \alpha_i)$.

The practical importance of equation (5) is that it shows that less absorbing material is necessary to obtain a definite (short) reverberation time than was to be expected according to the old formula, because at a definite value of α

$$-\ln (1 - \alpha) = \frac{\alpha}{1} + \frac{\alpha^2}{2} + \frac{\alpha^3}{3} \ldots\ldots > \alpha,$$

and therefore the denominator has the same value for smaller values of S_i.

Derivation of the formula for the mean free path

Let us first derive the formula for the special case of a sphere with the source of sound B at the wall and with total reflection (*fig. 6*). Each sound ray which leaves B at an angle α with the diameter, will after reflection at a point A again make an angle α with the diameter through A. This will be repeated. Each ray keeps its original length of path. We may, therefore, take the average of all chords, starting from B, and will then obtain the correct answer. We now assume that the source of sound radiates according to Lambert's cosine law. In this case the amount of direct sound per unit of area is the same at all parts of the spherical wall. (This recalls the sphere of Ulbricht in which for the same reason every element of the surface is equally intensely lighted by the light which is radiated from any arbitrary element of the surface).

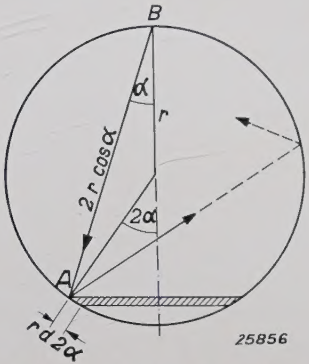

Fig. 6. Derivation of the mean free path.

The number of sound rays from B which make an angle α with the diameter is equal to the ring-shaped surface $2\pi r \sin 2\alpha \cdot r d(2\alpha)$. If we multiply this by the lengths of the chords $2r \cos \alpha$, we obtain $16 \pi r^3 \sin \alpha \cos^2 \alpha \, d\alpha$. If we now let α vary from 0 to $\pi/2$ and divide by $4\pi r^2$, we have the average length of path of the sound rays from B. This is

$$l = \int_0^{\pi/2} \frac{16 \pi r^3 \sin \alpha \cos^2 \alpha \, d\alpha}{4 \pi r^2} = \frac{16/3\ \pi r^3}{4 \pi r^2} = \frac{4V}{A} \quad \cdot \cdot \quad (4)$$

We can also derive formula (4) in a general way from a consideration of the kinetic gas theory. The derivation which follows is, however, only valid when we may assume that the space is uniformly filled with sound. We have previously derived that the energy falling upon 1 sq cm per second is $Ec/4$ in this case. For a gas in which n is the number of particles per cc the same derivation gives $nc/4$ for the number of particles which strike 1 sq cm per second. The number of particles which strike a surface A per second is then $ncA/4$. Let us consider a hypothetical surface which surrounds a volume V in the gas. Assume that the particles move in straight lines and do not collide with each other, and that the average path to the surface of each particle within the volume is l and its velocity c, then each particle remains l/c seconds in the volume V. If we now multiply the number of particles which strike the wall per second with this average time of remaining in the volume, it must give just the total number of particles in the volume. We obtain

$$\frac{n\,cA}{4}\cdot\frac{l}{c} = Vn \quad \text{of} \quad l = \frac{4\,V}{A}\,.$$

With a sufficient number of reflections, equation (4) is quite generally valid for the mean free path. If, however, the shape of the room or the position of the source of sound is not a very special one, so that the mean distance of the source of sound from the wall corresponds approximately with l, we shall also be able to use equation (4) for a small number of reflections, as was shown above for the spherical space.

Absorption by moisture of the air

In the foregoing we have spoken only of the absorption at the walls. For the higher frequencies there is also a volume absorption, that is, at very high frequencies energy is also absorbed from the sound waves by the air molecules themselves. Within the last few years it has been found that this absorption in the air is very dependent on the moisture in the air.

The influence of the water vapour seems to be based on the fact that it plays the part of a catalyst for the distribution of the energy over the possibilities of motion of the molecules. The absorption reaches a maximum at a definite small percentage of water vapour, which is dependent on the frequency. Above and below this percentage of water vapour the absorption decreases suddenly. If we indicate the absorption coefficient per metre for plane waves by m, a term $4\,mV$ occurs in the denominator of the formula for the reverberation time. This term is connected with the volume absorption. A derivation similar to that of equation (5) then gives

$$T = \frac{0.16\;V}{4\;mV - S\ln\,(1-a)}\,.$$

m is here a function of frequency and humidity. For frequencies below 1000 c/s m is so small that it may be neglected at all degrees of humidity, but above 5000 c/s the first term of the denominator may even become greater than the second. At frequencies above the limit of audibility the second term may be neglected in comparison to the first. For these frequencies the reverberation time in a reasonably large space becomes independent of the volume and the surface area of the space.

Reverberation time and intelligibility

From the preceding considerations we have seen that the sound intensity decreases exponentially after the source ceases to act. It is now plausible that the growth in intensity of sound from the moment the source begins to act is also exponential. We shall make use of this in order to explain the relation mentioned in the introduction between reverberation time and intelligibility.

Fig. 7 gives the growth and fading out of sound in a space with a reverberation time of 6 sec. The sound consists of spoken syllables, each of which lasts 0.15 second and which are separated by a time interval of 0.05 second. In the interval between syllables it is quiet. In the lower part of the graph we see the intensity time curves for the separate syllables. Each of these curves consists of two pieces of an exponential curve. The dotted curve is the integrated intensity, or better, the energy density proportional to it. The continuous upper curve represents the intensity which is obtained by continuous radiation of sound. From the dotted

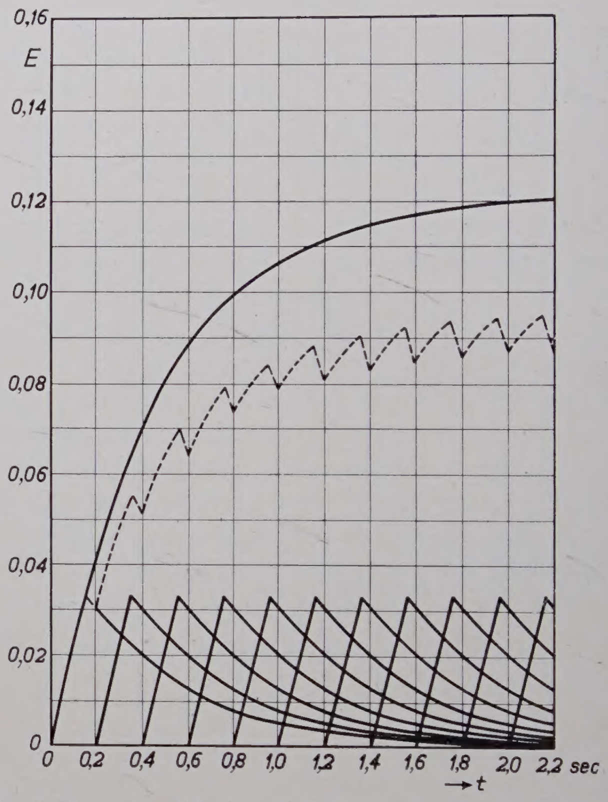

Fig. 7. Growth and fading of the sound in a space with a reverberation time of 6 sec. The sound consists of syllables which have a constant intensity for 0.15 sec and which are separated by intervals of silence of 0.05 sec. The intensity of the syllables projects only slightly above the average sound. The intelligibility is therefore poor.

curve it may clearly be seen that the individual syllables project only slightly above the average level of sound. It is therefore plain that the sound will be intense but not very intelligible. Let us now reduce the reverberation time of this space to 1 sec. by increasing the absorption (*fig. 8*). The intensity does not increase so rapidly, and there is sufficient fluctuation to make the syllables stand out clearly. *Fig. 9* gives the extreme case where there is practically no reverberation. The maximum intensity is that of the individual syllables. In this last case the speech is easily understood but the intensity is weak. We say of such a space that it is dead, and consider it in general unfavourable.

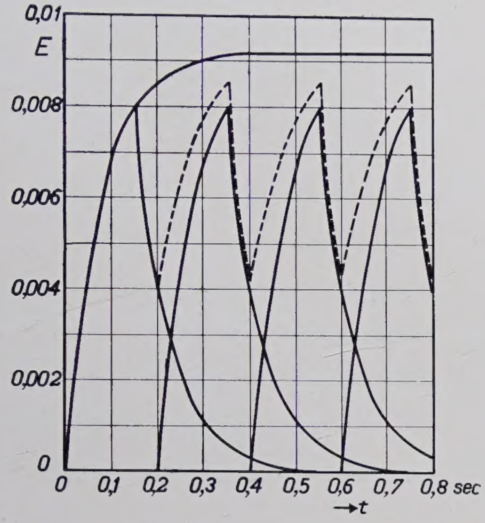

Fig. 8. Growth and fading of the sound in a room with a reverberation time of 1 sec. The individual syllables are well separated from each other. The intelligibility is good.

Final considerations

We shall briefly review the results given in the article.

The most important quantity for the acoustics of a hall is the reverberation time which must be 1 to 2 seconds according to the dimensions of the hall. This value of the reverberation time can be ensured in the design stage by providing a suitable relation between the volume of the hall and the area of the absorbing surface. The reverberation can be calculated by means of formula (1) or (5).

If a hall is very long or has an irregular shape, the calculation of the reverberation by formula (1) or (5) may give very inaccurate results. In such cases one is often concerned experimentally not with one definite reverberation time, but, for example, with two, as the recordings reproduced in figs. 2 and 3 show. The sound first decreases rapidly; the final fading out on a lower level then takes place more slowly. We have not gone deeply into such phenomena since they will not occur in a hall with good acoustics. For good acoustics it is necessary that the sound intensity be about equal everywhere in the room, that is, that the sound be distributed evenly throughout the whole space. This was, however, just the assumption which had to be made in order to derive Sabine's formula. If the acoustics of a hall are good, Sabine's formula. is therefore also satisfied.

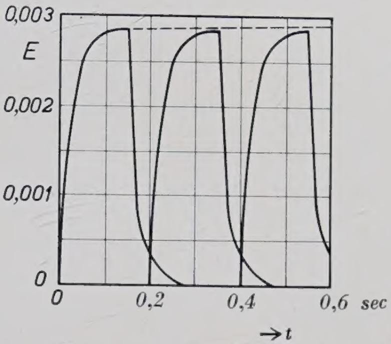

Fig. 9. Growth and fading of sound in a room with a reverberation time of 0.3 sec. The syllables are exaggeratedly separate from each other.

BARRETTERS

by J. G. W. MULDER.

621.316.72

In this article a study is made of the way in which the current regulating function of a regulator barretter is connected with the variation of the electrical resistance and the heat dissipation of a filament as functions of the temperature. The most satisfactory regulation curves can be obtained with an iron filament in an atmosphere of hydrogen at low pressure. Different forms of construction of Philips barretters are discussed. Finally several points are discussed which are important in the application of barretters to electrical installations. For the sake of illustration, the decrease in the current fluctuations in a tungsten lamp, a constant resistance and a carbon filament lamp are studied in connection with the loss of voltage in the preceding barretter.

Introduction

Barretters have been used in electrical engineering for many decades for the purpose of decreasing the current fluctuations which appear in electric circuits as a result of variations in the mains voltage or of changes in the load applied. An urgent need of such a current regulator was first experienced about 1900 when Nernst lamps were connected to power mains. The incandescent element of the Nernst lamp (thorium oxide) has a strongly negative temperature coefficient of the electrical resistance. If as a result of a small increase in voltage the current $I = V/R$ becomes somewhat larger, the resistance R decreases because of the corresponding increase of temperature, so that the current and the temperature continue to rise. If there were no resistance at all in series with the lamp, the current would continue to grow because of this instability until the element fused.

In order to avoid this unstable behaviour a resistance is connected in series with the Nernst lamp, which resistance varies with the temperature in exactly the opposite way to that in which the resistance of the element of the Nernst lamp varies. As early as 1899 it was found that an iron filament in an atmosphere of hydrogen was very suitable for this purpose. Iron was used because it has the highest positive temperature coefficient of the resistance, while hydrogen was originally chosen to protect the iron from oxidation. It was found later also that the heat conduction of the gaseous hydrogen is of importance.

As an illustration of the action of a current regulator the current voltage characteristics of two different barretters are shown in *fig. 1.* In example *a*), which may be considered a normal case, the current remains practically constant with a threefold increase of the voltage. In example *b*) there is even a falling back of the characteristic over a definite voltage interval, thus a decrease in the current with increasing voltage, and at the end of the regulation range the voltage is five times as great as in the beginning of that range.

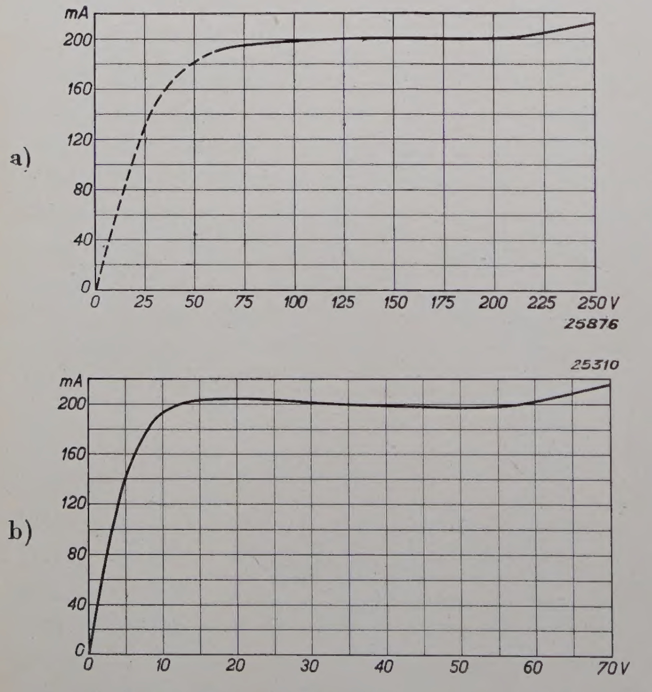

Fig. 1. Current through two barretters as a function of the voltage.
a) Normal type.
b) Type with exceptionally wide regulation range.

In the course of years the Nernst lamp has been displaced by better sources of light. Barretters on the above-described principle have, however, continued to be used, and are finding continually wider application for the most divergent purposes. The iron filament lamp, as has already been mentioned in this periodical, is used as the series resistance of gas discharge lamps, where it fulfils exactly the same function as in the Nernst lamp. A barretter is, however, sometimes also connected in series with ordinary incandescent lamps, where it is necessary to provide for large fluctuations of the mains voltage as on railways. There are, moreover, other applications in electrical engineering, such as for maintaining the constancy of the heating current of radio valves and of the charging current of batteries.

How is a flat current-voltage characteristic obtained?

If we assume that the filament has the same temperature over its whole length, we can easily calculate the relation between I and V, when the energy loss (radiation plus heat conduction plus convection) A, and the electrical resistance R as functions of the temperature T are known. We have the relations

$$\left.\begin{aligned} V\cdot I &= A(T) \\ V/I &= R(T) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (1)$$

A depends upon the nature and pressure of the gas and upon the external temperature; R is a property of the material of the wire.

The first equation expresses the fact that the state is stationary; the energy supplied is equal to that given off. The second is simply Ohm's law.

From these two equations it follows that

$$\left.\begin{aligned} \text{a)}\quad V &= \sqrt{A\cdot R} \\ \text{b)}\quad I &= \sqrt{A/R} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (2)$$

By calculating V and I for a number of temperatures we thus obtain an I-V curve. The following calculations are based on measurements of the heat dissipation of very thin wires in hydrogen gas by **Busch** [1]) and on resistance measurements of very pure iron by **Potter** [2]).

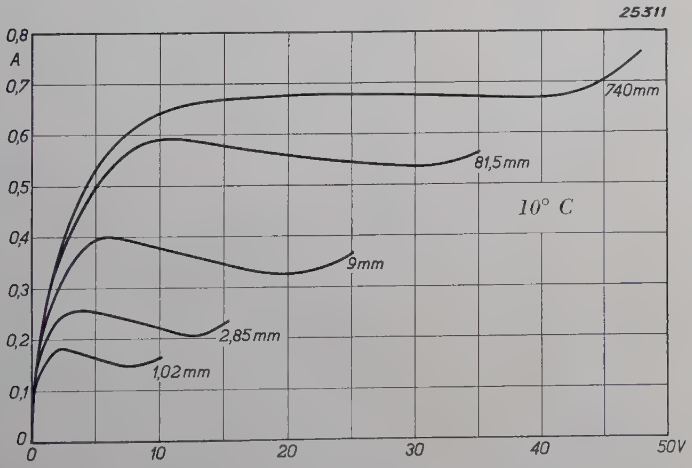

Fig. 2. Calculated I-V curves for an iron filament in hydrogen at different pressures. In a certain voltage interval there is a decrease of the current with increasing voltage.

The diagrams reproduced in *fig. 2* refer to a constant external temperature of 10° C and various pressures of the hydrogen. In *fig. 3* the characteristics are reproduced for a constant amount of hydrogen in the valve (25.8 mm Hg at 20° C) and three different external temperatures. The surprising result of these calculations is that the I-V curve for a given voltage reaches a maximum and then exhibits a falling back over a long range of voltages. The falling back of the characteristic is more pronounced the lower the external temperature.

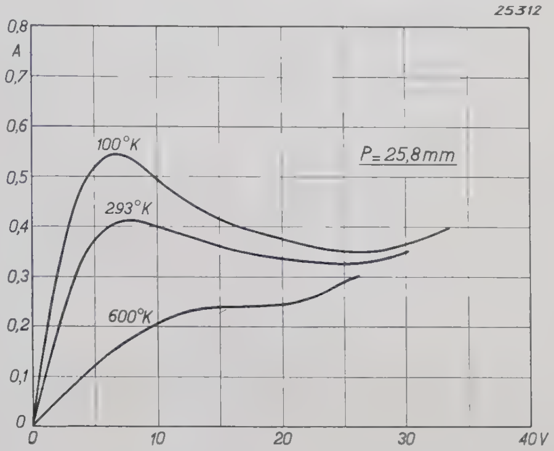

Fig. 3. Calculated I-V curves for a hydrogen pressure of 25.8 mm Hg at three different temperatures. With increasing external temperature the fall of the characteristic is less pronounced.

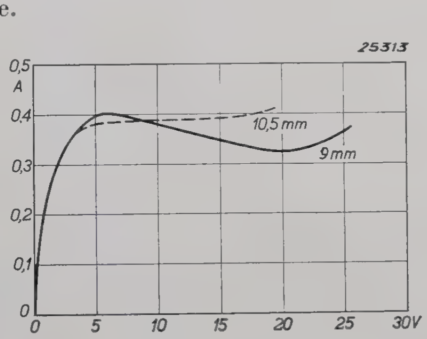

Fig. 4. Comparison of a calculated characteristic (fig. 2, 9 mm Hg) with a recorded characteristic under about the same conditions. The general shape is well confirmed. The descending portion, however, cannot be realized, because a uniform temperature is not established in this portion.

Fig. 4 shows, in addition to the curve for 9 mm pressure of *fig. 2*, an experimental curve for the same conditions. The general behaviour of the calculated curve is well confirmed; the falling back of the characteristic is, however, not present. The cause must be sought in the fact that a uniform distribution of temperature over the whole length of the wire, as was assumed in the calculation of the I-V curve, is not stable in the descending portion of the characteristic.

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[1]) H. **Busch**, Ann. Physik **64**, 401, 1925.

[2]) H. H. **Potter**, Proc. Phys. Soc. **49**, 671, 1937.

If we allow the temperature of a given element of the wire to rise slightly, not only the heat dissipation increases, but also the resistance and the supply of heat. In the descending portion of the *I-V* curve the supply of heat is found to increase more rapidly than the dissipation of heat, so that the temperature of the element continues to increase while the rest of the wire cools off when the voltage on the wire is kept constant.

The shape of the *I-V* curve is very sensitive to accidental factors. The parts of the wire which will become hotter, and how much hotter they will become, and the parts which will become cooler depend upon very slight irregularities in the state of the surface of the wire. The heat conduction along the wire is also important in this connection since it works to decrease the irregularity in the distribution of temperature along the wire. We shall not go more deeply into this very complicated problem.

What kinds of wire and what gases are suitable for use in barretters?

We shall now examine the conditions which must be satisfied if the current is to remain constant over a certain interval of temperature. The answer is implicit in equation (2).

By setting the first differential of the current with respect to the temperature equal to zero, we obtain:

$$\left.\begin{aligned} R\frac{\mathrm{d}A}{\mathrm{d}T} - A\frac{\mathrm{d}R}{\mathrm{d}T} = 0; \\ \text{and therefore} \qquad \\ \frac{T}{A}\frac{\mathrm{d}A}{\mathrm{d}T} = \frac{T}{R}\frac{\mathrm{d}R}{\mathrm{d}T} \end{aligned}\right\} \quad . \; . \; . \; . \quad (3)$$

In order to make the significance of this equation somewhat clearer, we can let A and R approach a certain working point T_0 by definite powers of the temperature:

$$A = A_0 \left(\frac{T}{T_0}\right)^{a},$$

$$R = R_0 \left(\frac{T}{T_0}\right)^{\varrho},$$

and therefore

$$I = \sqrt{A_0/R_0} \left(\frac{T}{T_0}\right)^{1/2\,(a-\varrho)}.$$

The requirement of a constant current thus comes down to the condition that $a = \varrho$.

The exponent ϱ of the resistance is approximately equal to unity for ordinary metals. a should be about 4 when the heat dissipation takes place by radiation. With heat dissipation by convection, a may be smaller, but it always remains considerably greater than one. The result is that a constant current is only possible when care is taken *that the resistance increases with an extraordinarily high power of the temperature, and the heat dissipation increases with an extraordinarily low power of the temperature.*

The metals iron and nickel, which show exceptionally high temperature coefficients of the electrical resistance somewhat above the magnetic Curie points, may in the first place be considered as materials for the filament. The values of $T/R\ \mathrm{d}R/\mathrm{d}T$ lie in a suitable temperature range between 2 and 2.5.

In contrast to the heat radiation, which increases with the fourth power of the temperature, heat conduction and convection, especially with great differences in temperature between filament and gas, show a much slower increase with temperature. By using a light gas, such as hydrogen, the conduction can be made to dominate over the radiation and the lowest possible value of $T/A\ \mathrm{d}A/\mathrm{d}T$ is thus obtained.

In order to obtain some idea of the suitability of different materials and gases, the quantities $T/R\ \mathrm{d}R/\mathrm{d}T$ (continuous lines) and $T/A\ \mathrm{d}A/\mathrm{d}T$ (dotted lines) are shown for these materials and gases in *fig.* 5 as functions of the temperature.

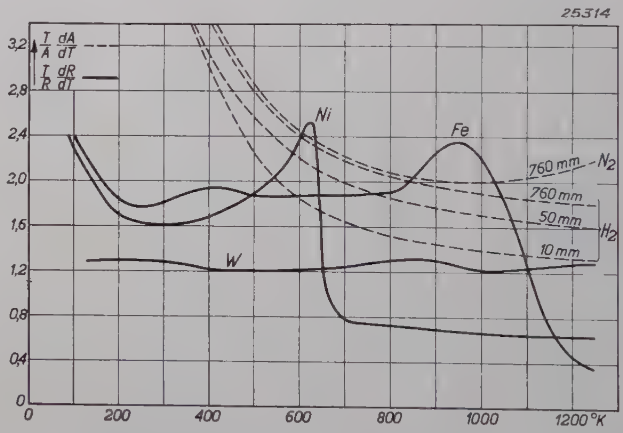


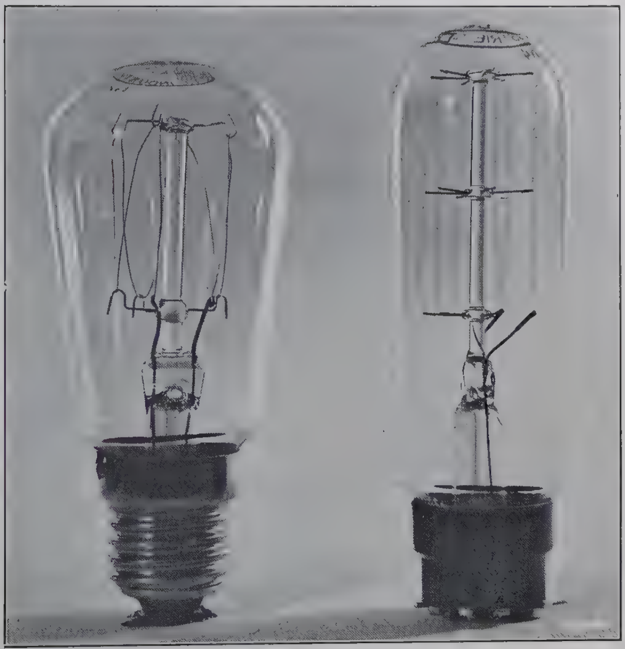
Fig. 5. Continuous lines: $T/R\ \mathrm{d}R/\mathrm{d}T$ values of different metals as a function of the temperature (R, electrical resistance, T absolute temperature). Dotted lines: $T/A\ \mathrm{d}A/dT$ values of a very thin wire for different gases and pressures (A heat dissipation of a wire in this gas). In the range where a continuous line lies above a dotted one, the corresponding combination of metal and gas shows a descending characteristic. The greatest descending range is that of an iron wire in an atmosphere of hydrogen at a pressure of 10 mm.

If a continuous line and a dotted line intersect, the combination in question of filament material and gas produces a descending *I-V* curve. In the temperature range between 850° K and 1100° K the $T/A\ \mathrm{d}A/\mathrm{d}T$ value for nitrogen lies relatively close to the $T/R\ \mathrm{d}R/\mathrm{d}T$ value of iron. In this range therefore an iron filament in nitrogen at ordinary pressure would be suitable as a current regulator. In the case of most metals the resistance is about proportional to the temperature

$(T\ R\ \mathrm{d}R/\mathrm{d}T\quad 1)$, which is too low for the production of a flat *I-V* curve. At very high temperatures the temperature coefficient of heat dissipation in hydrogen and other light gases is so low that it approaches the temperature coefficient of the electrical resistance of tungsten. It has actually been found possible to construct a barretter with tungsten in helium.

Some details of the construction of Philips' barretter

The desired favourable conditions for cooling are best realized by a straight wire. In order to avoid difficulty in construction, however, the wire is usually suspended in a zigzag form (*fig. 6a*) or in the form of a spiral (fig. 6*b*). This has practically no objectionable effect if care is taken that the surface of the bulb is not too small for the energy dissipated. If it is desired to obtain a long range of regulation the surface of the bulb must be at least several sq.cm/watt.



a) b)

Fig. 6. Barretters.
a) The filament is suspended in a zigzag form.
b) The filament has the form of a spiral.

With a given diameter of the tube and a given diameter and temperature of the filament, an increase in the heat dissipation can be attained by making the cross section of the filament and/or of the tube flattened instead of circular. This possibility is successfully utilized in regulators for heavy currents with relatively small dimensions. In such valves the heat dissipation is naturally often insufficient so that the regulation range is relatively short. *Fig. 7* gives an example of the way in which the regulation curve is improved when the circular wire is replaced by a flat strip.

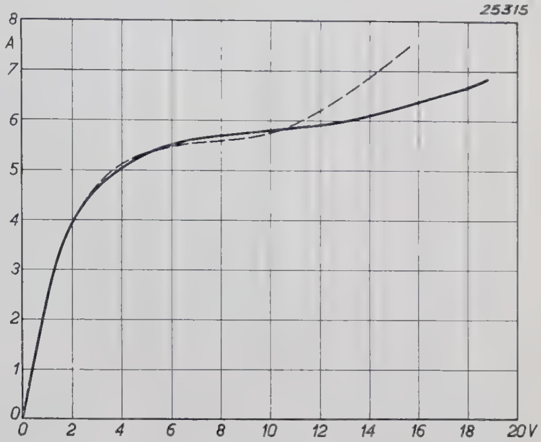


Fig. 7. *I-V* curve of a barretter, dotted line: filament with circular cross section; continuous line: flattened filament (thickness $^1/_{30}$ of breadth). The improvement in the conditions for cooling resulting from the flattening has resulted in an increase of the range of regulation.

Special measures were necessary in the construction of regulator valves for low currents. If such a valve with a filament of pure iron is connected to the alternating current mains, it is observed that the filament shrivels, as a result of the temperature fluctuations, and becomes so short that it quickly breaks. In order to prevent this happening, care must be taken that the transition point between the α-modification and the γ-modification of the iron is not passed through during the fluctuations in temperature. *Fig. 8* shows two iron filaments each of which has repeatedly been heated to red heat, that on the left just below, that on the

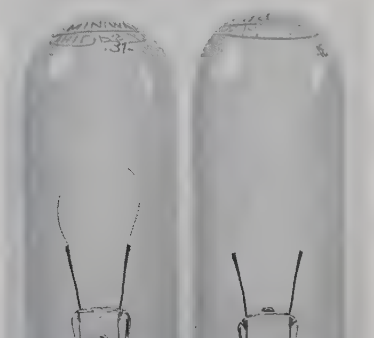


Fig. 8. The iron filament in the left-hand lamp was heated 50 times to 900° C, that in the right-hand lamp 25 times to 1150° C. The latter is very much shrivelled and shortened, while the first has remained absolutely smooth. The cause of the shrivelling lies in the fact that there is a phase change at 906° C of the iron between the α-modification (lower temperature) and the γ-modification (higher temperature).

right just above the transitionpoint (906 °C). The left-hand filament is quite smooth and bright, the right-hand one is badly shrivelled.

With filaments of a nickel-iron alloy, which has no transition phase, these difficulties are not encountered, and current regulators with low regulation current can be made for alternating current also. The relation between the maximum and the minimum voltage of the regulation range need only be slightly less favourable with these barretters than with those having pure iron filaments.

Circuits containing barretters

Since the current in the regulation range of the barretter lamp is fixed, a separate type of lamp must be used for each current. There is in principle no limitation of the current. It is, however, advisable to use several lamps in parallel for currents greater than 6A, because the heating up time of 6A barretters is several seconds, and increases approximately with the square of the current.

For different regulation ranges of the voltage a separate type of valve is also necessary. The voltage, however, need not be adjusted so accurately as the current; it is only necessary that the variations in voltage occurring fall within the regulation range of the valve. Barretters are made with voltages up to 240 volts in the middle of the regulation range. The connection of several lamps in series is not immediately possible. If the barretters do not have exactly the same current in the regulation range, then, when I is the current through both, the barretter lamp with characteristic a (*fig. 9*) will adjust itself to the working point P, and the tube with the characteristic b to point Q. This destroys any possibility of regulation, because at the moment when lamp a assumes its regulatory function, b is already fully loaded and every further increase in the load damages barretter tube b.

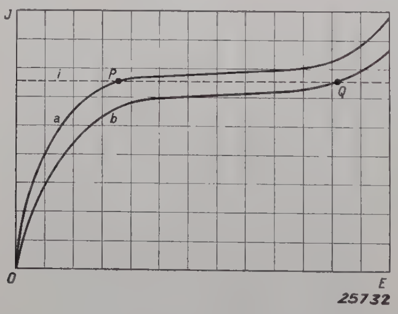


Fig. 9. Two barretter lamps of the same type with slightly differing characteristics may have quite different working points P and Q at the same current. Because of this regulator lamps may not be connected in series.

Two applications of Barretters

As an example ³) of the application of barretters let us try to decrease the current fluctuation of a tungsten lamp, a carbon filament lamp or a constant resistance on a variable mains voltage. To do this, we represent the V-I characteristic of the regulator at the working point by the equation

$$\frac{\Delta V_r}{V_r} = q \frac{\Delta I}{I} \quad \ldots \ldots \ldots \ldots \quad (4)$$

For a constant resistance $q = 1$; for an absolutely flat characteristic $q = \infty$. We shall take the rather low value of $q = 10$ for the resistance tube, which is therefore not a very flat I-V characteristic. For the voltage V_{gl} on the load, for example an electric lamp, a similar equation holds

$$\frac{\Delta V_{gl}}{V_{gl}} = p \frac{\Delta I}{I}, \quad \ldots \ldots \ldots \ldots \quad (5)$$

where p, for tungsten filaments for instance, is about equal to 2, and for carbon filament lamps is about 0.7. From (4) and (5) it follows that

$$\frac{1}{p} \frac{\Delta V_{gl}}{V_{gl}} = \frac{1}{q} \frac{\Delta V_r}{V_r} \quad \ldots \ldots \ldots \quad (6)$$

Now the total variation in the voltage of the mains is

$$\Delta V = \Delta V_{gl} + \Delta V_r, \text{ or according to (6)}$$

$$\Delta V = \Delta V_{gl} + \frac{q}{p} \frac{V_r}{V_{gl}} \Delta V_{gl},$$

from which it follows that

$$\frac{\Delta V_{gl}}{V_{gl}} = \frac{\Delta V}{V} \frac{p V}{p V_{gl} + q V_r},$$

$$\frac{\Delta V_{gl}}{V_{gl}} = \frac{\Delta V}{V} \frac{1}{1 + \left(\frac{q}{p} - 1\right) \frac{Vi}{V}} \quad \ldots \quad (7)$$

The relative voltage fluctuations on the lamp are thus decreased more, the greater the portion V_r/V of the mains voltage destroyed by the regulator. In *Table I* are given several numerical values for $q = 10$; $p = 2$, $p = 1$ and $p = 0.7$.

If a barretter is used which takes up half of the voltage ($V_r/V = 0.5$), the voltage fluctuations of an ordinary electric lamp, a constant resistance and a carbon filament lamp are reduced to 33, 18 and 13 per cent respectively.

---

³) N. A. Halbertsma, Elektrotechn. Z. **48**, 512, 1927.

Table I.

V_r/V	$\frac{\Delta V_{gl}}{V_{gl}} : \frac{\Delta V}{V}$		
	$p = 2$	$p = 1$	$p = 0{,}7$
0.0	1.000	1.000	1.000
0.1	0.714	0.526	0.429
0.2	0.556	0.357	0.273
0.3	0.455	0.270	0.200
0.4	0.384	0.218	0.158
0.5	0.333	0.182	0.131
0.6	0.294	0.156	0.111
0.7	0.263	0.137	0.097
0.8	0.238	0.122	0.086
0.9	0.217	0.110	0.077
1.0	0.200	0.100	0.070

The considerations above refer only to stationary working states. When a starting current surge occurs, it is usually not decreased by the current regulator, and in some cases it is even reinforced, since the cold resistance of the barretter is very small.

In the stabilization of the heating current in some radio sets it is necessary to take precautions against these starting surges. In these sets there is a small lamp for lighting the tuning scale connected in series with the heating filament of the indirectly heated cathodes. This lamp has a much smaller heat capacity and might burn through in the time necessary for the indirectly heated cathodes to heat up. For the stabilization of this heating current a special stabilizing resistor has been constructed which has a semi-conductor as limiting resistance in series with the filament. The size of this resistance is about 2000 ohms at room temperature; when, however, it is raised to 300° C by the heat of the current, only 100 ohms of the resistance remain [4]).

Upon switching on the set the current is limited by the resistance of the semi-conductor to a small portion of its running value. During the heating up of this resistance the iron filament also becomes warm and assumes its regulatory function so that the current never reaches too high a value.

The action of a semi-conductor in series with the regulator valve is made clear in *fig. 10.* The upper curve gives the variation of the current upon switching on the heating current without a limiting resistance, the lower curve shows the variation of the same when a starting resistance is used. In the first case the starting surge is about four times the running current, while the current reaches 10 per cent more than the running value at its maximum when a starting resistance is used, and reaches its stationary value only after several seconds. In this final state the greater part of the resistance of the valve is due to the iron filament, and only a small part is due to the semi-conductor, so that the regulatory action of the iron filament is manifested, and the current remains constant within narrow limits when the mains voltage fluctuates.

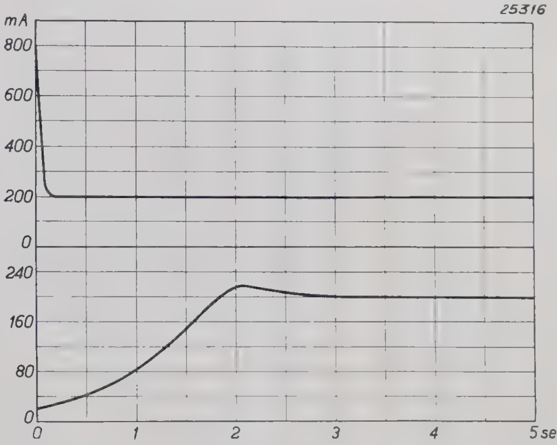


Fig. 10. Variation of the heating current in a radio receiver with receiver valves heated in series as a function of the time after switching on. Above: an ordinary barretter is in series with the filaments. Below: a regulator with a semi-conductor incorporated in it is in series with the filaments. The resistance of the semi-conductor has a very high value in the cold state, and therefore limits the starting surge of the current.

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[4]) Resistors of this material are also used as starting resistances for motors, and have already been described in this periodical by P. C. van der Willigen, Philips techn. Rev. **1**, 205, 1936.

SECONDARY ELECTRON EMISSION

by H. BRUINING.

537.533.8.

A discussion is given of the properties upon which the capacity for secondary emission of materials and surfaces is based. A special study is made of the choice of material in cases where, for the purpose of technical application, either a very large or a very small secondary emission is required.

Introduction

When a material, either a metal or a dielectric, is bombarded by electrons having a certain speed, a small portion of these electrons is reflected. The greater portion penetrates into the layer which is bombarded, and passes on its energy to the electrons present in that layer; the latter electrons may, when the direction of their motion is favourable, leave the bombarded surface. We are then concerned with secondary electrons. They can be observed when an electrode capable of capturing the electrons emitted is placed in the neighbourhood of the secondary emitting surface.

In all tubes in which surfaces are struck by electrons we are concerned with the phenomenon of "secondary emission". Among such are radio valves, cathode ray tubes and the like. There are a number of cases in which the secondary emission is a disturbing factor, so that efforts are made to suppress it, for example: the secondary emission of anode and screen grid in a tetrode, the secondary emission of the glass wall, the secondary emission of the grid of a broadcasting valve. On the other hand there is the possibility of making use of a high secondary emission; a well known application is the amplification of the electron current as in the electron multiplier and the secondary emission valve. A high secondary emission is further of importance in the fluorescing screens of cathode ray tubes and for the anode in the so-called dynatron. The technical application of secondary emission will be discussed in more detail in a subsequent article. The intention of the examples just given is only to make clear that it is important to be able to prepare substances which emit either very many or very few secondary electrons. We shall discuss in this article the laws of secondary emission so that it may be possible to make a choice of materials for technical applications.

Determination of the capacity for secondary emission

The capacity for emitting secondary electrons is always expressed in the number of secondary electrons, which are freed on the average by one primary electron. We shall indicate this ratio by the letter δ. The factor δ was determined in this laboratory for a large number of materials with the help of the apparatus shown in *fig. 1* 1)). It consists of a glass tube without cement or grease

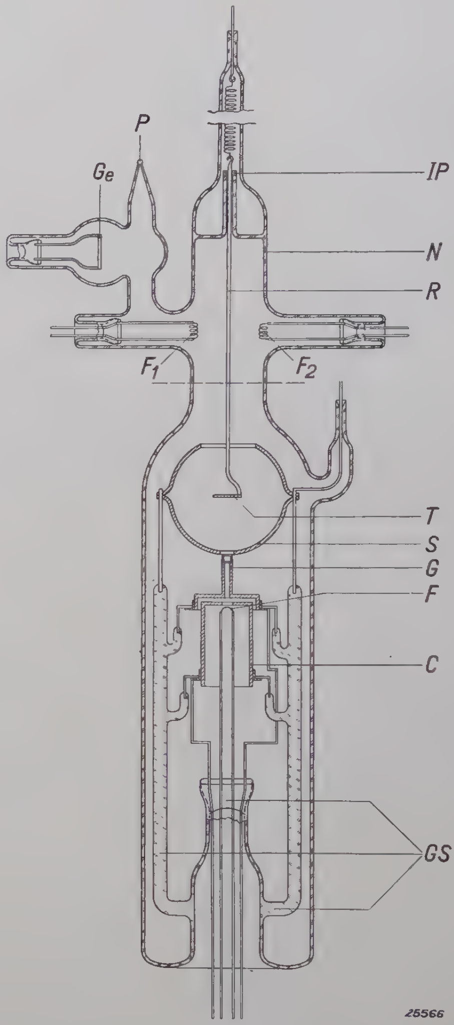

Fig. 1. Tube for the measurement of secondary emission of different materials.

F = cathode, source of primary electrons.
C = cylinder.
G = electron gun.
T = target whose secondary emission is to be determined.
S = sphere, collector for the secondary electrons.
GS = bridge upon which F, C, G and S are mounted.
R = rod.
IP = iron cylinder attached to R. By means of a magnet around IP the target can be drawn into the neck N of the tube.
N = neck of the tube.
F_1F_2 = tungsten filaments, by means of which the target T can be covered by sublimation with the substance to be examined.
Ge = plate from which getter can be evaporated.
P = point where the tube is sealed off.

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1) See also H. E. Farnsworth, Phys. Rev. **25**, 41, 1925.

joints. The tungsten filament F is the source of the primary electrons. This is surrounded by a cylinder C which concentrates the electrons on the opening of the canal G. The electrons passing through the aperture of C are gathered into a beam by the electron gun G which strikes the target T. The secondary emission of T is to be determined. The secondary electrons are collected on the sphere S, and the strength of the electron current to S is measured. For this purpose the potential of S must be slightly higher than that of T (10 volts is usually chosen as the potential difference). The target T can be covered with different materials. For this purpose it is attached to a rod R at the extremity of which a piece of iron IP is fastened which makes it possible to draw the target into the neck N of the tube by means of a magnet. The substances to be investigated are applied to heating spirals F_1, F_2, and can be deposited on the target by sublimation.

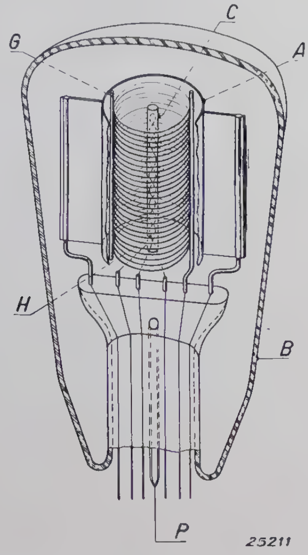

Fig. 2. Triode for measuring secondary emission.
C = cathode (indirectly heated, may also be tungsten wire).
H = heating filament of C.
G = grid.
A = anode.
B = wall of bulb.
P = connection to pump.

It is also possible, though with less accuracy, to determine secondary emission by means of a triode (*fig. 2*). The cathode C, heated by the spiral filament H supplies the primary electrons. The substance to be investigated is applied to the inner side of the anode A, while the grid potential V_g is chosen higher than the anode potential V_a, so that the secondary electrons are drawn from the anode to the grid G. A part si_k of the primary cathode current i_k will be captured immediately by the grid, and the current $(1-s)\,i_k$ will reach the anode. This latter will cause a current i_s of secondary electrons. If δ is the coefficient of the secondary emission of the anode surface, then

$$i_s = \delta\,[(1-s)\,i_k)] \quad \cdots\cdots \quad (1)$$

δ may be determined by measuring the grid current and the anode current separately. The anode current is

$$i_a = (1-s)\,i_k - i_s \quad \cdots\cdots \quad (2)$$

The grid current is

$$i_g = s\,i_k + i_s \quad \cdots\cdots \quad (3)$$

By eliminating i_k and i_s in the equations (1), (2) and (3) we find

$$\delta = 1 - \frac{i_a}{(1-s)\,(i_g + i_a)}.$$

According to the above equation the anode current $i_a = 0$ corresponds to $\delta = 1$. This is immediately clear. If every electron which strikes the anode frees on the average one secondary electron, then no mean charge is given to the anode and the anode current disappears. With many materials δ is greater than one in a certain range of the anode potential, and a negative anode current is the result.

The fact that a portion (si_k) of the primary electrons are captured by the grid is a disadvantage, since the factor s is difficult to determine accurately. In the arrangement shown in fig. 1 this disadvantage does not exist, and the method is more accurate.

Energy distribution of the secondary electrones

With the apparatus shown in fig. 1 it is also possible to determine the energy distribution of the secondary electrons. If the potential of the

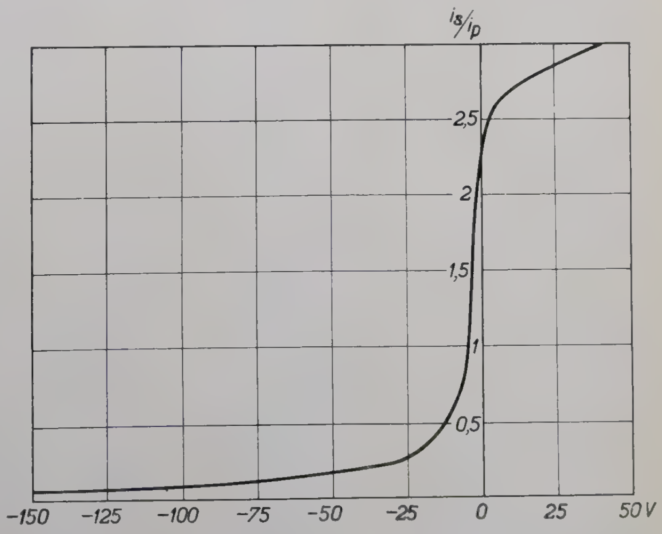

Fig. 3. Energy distribution of secondary electrons emitted by barium oxide.

sphere S is taken lower than that of T, all the electrons emitted by T cannot reach the sphere, but only those which are emitted with sufficient kinetic energy to overcome the applied counter potential. Thus if the potential of the sphere is for example 5 volts lower than that of the target, the sphere is struck only by secondary electrons with a kinetic energy greater than 5 electron volts. *Fig. 3* gives an idea of the results of such a measurement of the energy distribution obtained with barium oxide. The potential of the sphere S is plotted as abscissa, with the potential of T set equal to zero. The ratio of the secondary to the primary current i_s/i_p is plotted as ordinate. The intention of the figure in this case is to show that, when a secondary emission is desired, the electrode which must capture the secondary electrons must be at a higher potential than the secondary emitting layer itself. If, however, the desire is to avoid the capture of secondary electrons such a counter field must be applied that the transfer of electrons becomes impossible. It may be seen from the figure, for example, that in this case the secondary electron current decreases to 8 per cent of its original value when the potential of + 30 volts is reduced to — 30 volts with respect to the target T.

The relation between δ and the energy of the primary electrons

Figs. 4 and *5* show the dependence of the secondary emission δ on the potential difference V_p between the cathode and the secondary emitting target for different substances. It may be seen that δ as a function of V_p exhibits a maximum. The occurrence of this maximum must be explained in the following way. With increasing potential the number of secondary electrons freed in the metal will increase, since the available energy present per primary electron becomes greater. On the other hand the primary electrons will penetrate deeper into the material with increasing velocity, so that the secondary electrons are freed at greater depths, and are therefore more strongly absorbed before they reach the surface. At a large value of V_p the absorption apparently dominates to such a degree that the curve shows a maximum. By means of an experiment which will not be described here 2) we have estimated the average depth at which the secondary electrons are freed to be at least 20 layers of atoms in the case of nickel at V_p = 500 volts.

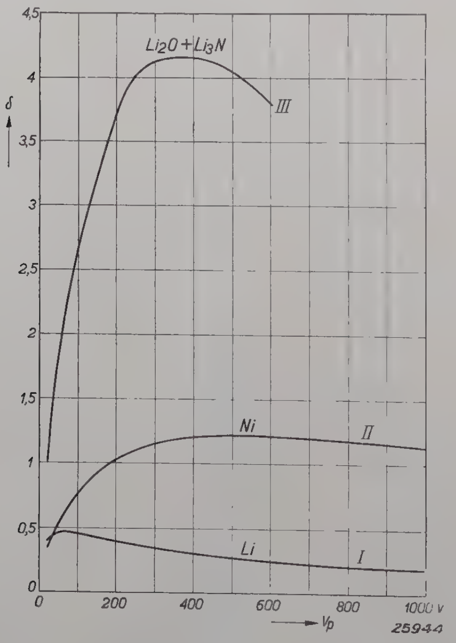

Fig. 4. Secondary emission of:
I lithium deposited by sublimation in a high vacuum.
II nickel.
III lithium deposited in the presence of residual gases.

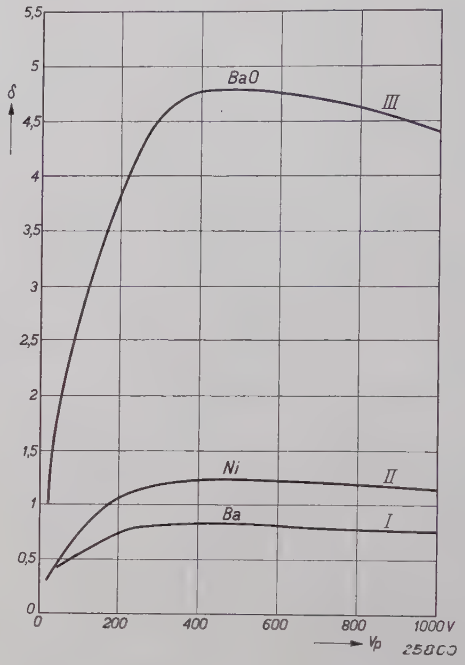

Fig. 5. Secondary emission of:
I barium deposited in a high vacuum
II nickel
III barium oxide

Substances with a high secondary emission

In this section we shall discuss the substances

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2) H. Bruining, Physica **3**, 1046, 1936.
For other investigations of this subject by the writer the reader is referred to:
H. Bruining and J. H. de Boer, Physica **4**, 473, 1937.
H. Bruining and J. H. de Boer, Physica **5**, 17, 1938.
H. Bruining, J. H. de Boer and W. G. Burgers, Physica **4**, 267, 1937.

which can be used when a high secondary emission is required. The requirement made of these materials is that they be able to give a secondary current which is at least three times the primary current, in other words, that the factor δ be at least 3. We shall compare the various surfaces with regard to the factor δ in their behaviour when bombarded with primary electrons with an energy of 150 electron volts, since 150 volts is a suitable working voltage for the acceleration of the primary electrons.

The metals most commonly used in discharge tubes do not have a high secondary emission. As may be seen from fig. 4, for nickel $\delta = 0.94$ when $V_p = 150$ volts, so that it is impossible in this way to multiply electrons, that is to obtain more secondary than primary electrons. Other metals also of which electrodes may be made, such as copper, iron, molybdenum and tungsten, are useless for the same reason.

The secondary emission of all these metals is practically the same. This is not to be wondered at, since the work necessary to bring an electron out of the metals is of the same order of magnitude (4—5 volts) for all these materials. The question immediately arises as to the behaviour of metals with lower work functions. Known representatives of this group are the metals of the alkali metal group, Li, Na, K, Rb and Cs, and the alkaline earth metals, Be, Mg, Ca, Sr and Ba. Much less energy is necessary to cause an electron to leave these metals, as may be seen from the photoelectric and thermionic emission. It has often been assumed that the secondary emission is analogous in its behaviour, so that the factor δ of the alkaline earth metals should be larger than that for instance of Ni and Mo. *It is found, however, that metals with a low work function, at least in the* V_p *range with which we are concerned, have a lower secondary emission than the metals with a high work function.*

In figs 4 and 5 the variation of δ as a function of V_p is given for Li and Ba (curve *I*). Curves *II* give, for the sake of comparison, the variation of δ for nickel. This latter curve is reproduced in all figures up to *fig. 11.* The measurements on the metals Li and Ba, which readily form compounds with residual gases (oxides, nitrides) have been carried out with the greatest care. Every effort was made to obtain a good vacuum. If such measures are not taken, the results obtained are quite different, as may be seen from curves *III*. Curve *III* in fig. 4 refers to Li which was sublimed in a tube in which residual gases were still present, while curve *III* in fig. 5 refers to a layer of Ba which had been exposed to dry oxygen for some time and thus consisted mainly of BaO [3]).

The following conclusions may be drawn from these experiments.

1. *Secondary emission is determined by quite different factors than those which determine photoelectric and thermionic emission.*
2. The compounds of the electropositive elements form suitable surfaces for secondary emission, but the pure elements themselves do not.

Layers of the alkali halides deposited by sublimation have a high secondary emission. In *tables I* and *II* results are given which were obtained in an extensive series of experiments.

Table I. Secondary emission of metals at $V_p = 150$ volts.

Metal	δ	Work function in volts
Li	0.45 0.55	2.28
Cs	0.55	1.81
Be	0.52	3.16
Mg	0.90	2.42
Ba	0.63	2.11
Al	0.86	2.26
Cu	0.90	4.30
Ni	0.94	5.03
Fe	0.97	4.77
Mo	1.00	4.15
W	0.75	4.52

For practical use the secondary emitting substance must not only possess a good factor δ, but this value, moreover, must not change during emission. Many compounds with a high secondary

Table II. Secondary emission of compounds of electropositive elements at $V_p = 150$ volts.

Surface	δ
Li, sublimed in poor vacuum	3.25
NaCl	4.0
KCl	4.45
RbCl	4.15
CsCl	4.55
Cs, oxidized in dry oxygen	3-4
MgO	2-6 [4])
BaO	approx. 3
Al, covered with a thin layer of oxide	2.1

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[3]) The contention is often encountered in the literature that elements with a low work function are good secondary emitters. This idea is based upon results of measurements on (probably) oxidized surfaces.

[4]) With this surface, which consists of small particles, the factor δ is very much increased by the external applied field. This is more or less the case with all the compounds mentioned here, see fig. 3 for example.

emission have the property of decomposing during emission, and forming metal agglomerates, which naturally causes a fall in the value of δ. In this respect the most satisfactory results up to the present have been obtained with MgO whose δ value remains very constant with time. The alkali halides are useless in this connection.

Mechanism of secondary electron emission

In connection with the above-described results it is important to find out whether compounds of metals with a less pronounced electro-positive character also have a larger δ than the metals from which these compounds are derived. From *table III* it may be seen that this is not the case. We shall now discuss what we consider to be the reason for this.

Table III. Secondary emission of compounds of metals with a high work function at V_p = 150 volts.

Compound	Secondary emission	Secondary emission of the pure metal
MoS_2	0.9	1.00
MoO_2	~ 1	1.00
WS_2	0.77-0.85	0.75
Cu_2O	0.99-1.05	0.90
Ag_2O	~ 1	1.05

As already mentioned, a primary electron passes on its energy to the electrons present in the material, and therby loses its kinetic energy along its path through the material. The kinetic energy is not passed on to a single electron; it is lost by "stages"; several electrons receive an impulse from the primary electron.

In order to find out what happens to these electrons we shall first consider a simpler case and recall experiments by Franck and Hertz. They studied what happens when the atoms of a gas or metal vapour are bombarded by electrons. In this case also the kinetic energy of the impinging electron is passed on to electrons of the material. It is found, however, that the latter electrons cannot take up every arbitiary amount of energy, but only very definite amounts. For example, the electrons of mercury atoms are unable to take up smaller amounts of energy than 4.8 electron volts. This is shown by the fact that electrons with a smaller energy suffer practically no loss of speed. Electrons which have passed through a somewhat greater potential difference than 4.8 volts, however, suffer a very great decrease in speed and their energy is for the greater part transformed into the well known ultra violet radiation of mercury vapour. If a beam of electrons falls upon a solid metallic compound a similar phenomenon takes place. There is a minimum amount of energy which can be taken up by the electrons. This amount is indicated by ε_1 in *fig. 6*. It will make a great difference whether this energy ε_1 is larger or smaller than the energy u which the electrons need in order to leave the metal (the so-called work function).

In the case of compounds of the alkali metals $\varepsilon_1 > u$ (fig. 6*a*). All electrons which have received an impulse from the primary electrons are thus accelerated enough to overcome the work function, and a large part of these electrons will actually leave the material. In the case of compounds of metals which are not strongly electro-positive $\varepsilon_1 < u$, and only the electrons which have received more energy than ε_1, for instance ε_2, from the primary beam, can take part in secondary emission. The factor δ is hereby considerably decreased.

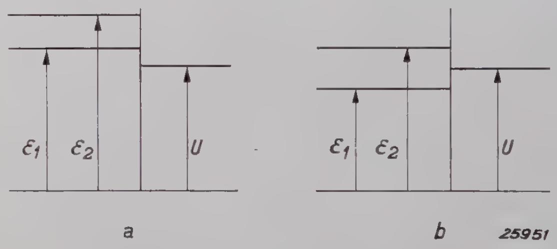

Fig. 6. a) The work function u of compounds of strongly electro-positive metals is lower than the minimum amount of energy ε_1, which can be passed on to the electrons in the solid substance.
b) With compounds of not strongly electro-positive metal $\varepsilon_1 < u$.

Materials and surfaces with only slight secondary emission

In the following we shall discuss substances and surfaces which have only a slight secondary emission. According to table I the metals lithium and beryllium must be especially considered in this connection. If these metals are used in tubes with a very high vacuum, they would indeed serve very well, especially at large values of V_p (of the order of magnitude of 1000 volts for example). During the experimental manipulations, however, there will always be residual gases present (from the oxide cathode, for instance) which combine with the lithium or beryllium and give in that way a substance with a large factor δ. In most practical cases a different kind of surface must therfore be sought.

In any case the choice will depend on the particular requirements made in practice. Thus for example for the grid of a transmitting triode (tetrode or pentode), it is necessary that the secondary emission does not become too great over the whole range of V_p [5]). The metal must, moreover, have a high melting point. Zirconium and titanium are suitable in these respects. Both metals still have more or less electro-positive characteristics, but they are covered with a very thin film of oxide when exposed to the air. Upon heating the oxide film is dissolved in the metal [6]), so that in a very simple way a metallic surface is obtained with a relatively low δ. The size of δ is shown in *fig. 7*. The secondary emission of a molybdenum or tungsten grid can also be decreased by covering it with a layer of ZrO_2, and heating it to a high temperature during evacuation. A zirconium surface is probably obtained by reduction of the ZrO_2.

Another method of keeping the secondary emission low is found in a suitable macroscopic structure of the surfaces. Up to now we have discussed only smooth surfaces. If a secondary electron has overcome the work function in the case of a smooth surface, it no longer encounters any material hindrances in its further motion (*fig. 8*). With a rough surface with a labyrinth-like structure the situation is different. In such a case there is the possibility that the electrons, after they have left the material, will again be captured by a projection of the rough surface.

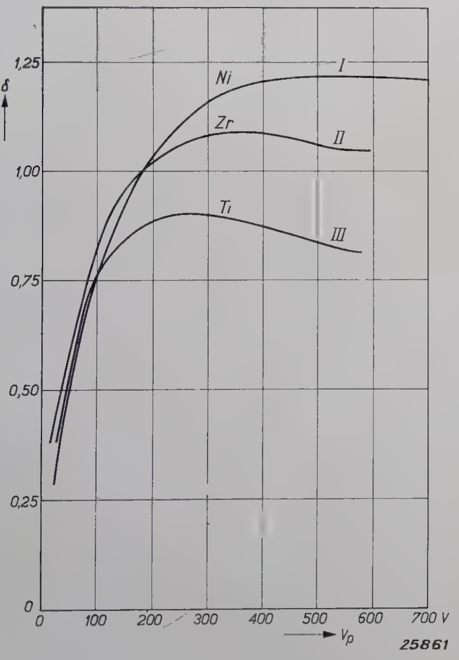

Fig. 7. Secondary emission of
I nickel
II zirconium
III titanium

There are numerous methods of preparing such "labyrinth" surfaces. The surface may for example be composed of very small particles forming a porous layer such as a layer of carbon black [7]). All carbon layers, however, do not have a porous structure. Smooth layers of carbon can also be prepared, for instance by painting a plate with aquadag, which gives a layer built up of overlapping flakes of graphite. *Fig. 9* gives a comparison of the factor δ as a function of V_p for a smooth and a rough carbon surface. From this figure it may clearly be seen that aquadag gives a greater secondary emission than carbon black.

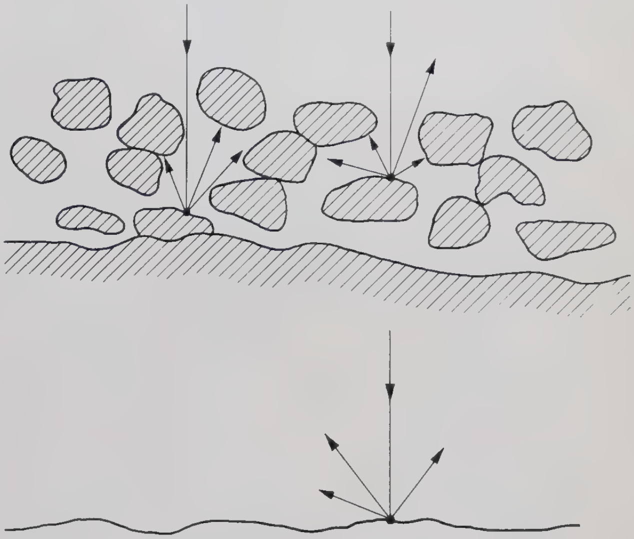

Fig. 8. Rough and smooth surfaces. In the case of the rough surface a portion of the secondary electrons are captured by the material itself, with the smooth surface they can escape unhindered.

It is possible to obtain other substances besides carbon in this "black" form; the same may be done with many metals. One method is by subliming the metal in question in an atmosphere of one of the rare gases. The atoms in the vapour state collide with the atoms of the gas and therefore cover longer paths before they condense on the wall. The metal will then form conglomerates in the gas which will be deposited as such on the surface. These conglomerates may reach a size of several millimetres. The surface then appears black. Metal deposited in a vacuum usually has a mirrorlike surface. *Fig. 10* gives an example of the difference in the secondary emission of silver deposited respectively in a vacuum and through an atmosphere of 1 mm of argon.

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[5]) If this factor is too large as in the case of most of the metals used for this purpose such as Ni, Mo, W and the like the grid current as a function of the grid voltage begins to show a negative coefficient of direction. See also H. G. Boumeester, Philips techn. Rev. **2**, 115, 1937.

[6]) This is not the case with the metals mentioned in table I.

[7]) In this section we discuss only conducting materials. With non-conducting materials, making the surface rough may cause an increase in δ.

The black layer formed is not stable to temperature in the case of many metals. During degassing at a high temperature the black modifications often have the tendency to sinter (baking together of the small particles to larger ones), whereby the labyrinth structure disappears. The surface then becomes grey. The sintering temperature is much lower than the melting point, but runs parallel to it when the metals are compared among themselves. In general use must be made of metals with a melting point higher than 2000° C. In this respect the black forms of tungsten and molybdenum are particularly suitable. Carbon black also, because of the high melting point of carbon, has a high sintering temperature, but has the disadvantage of often giving off much gas and of dissolving rapidly in nickel at about 1000° C.

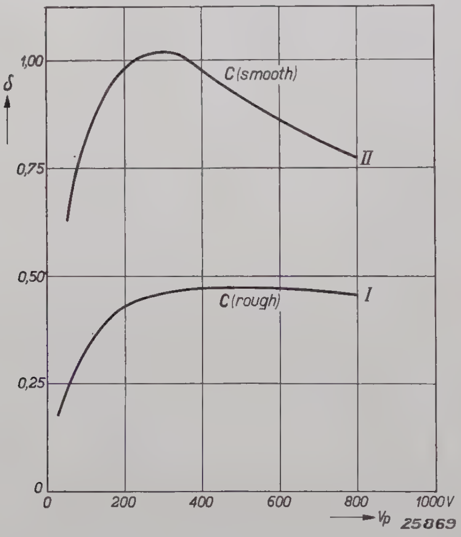

Fig. 9. Secondary emission of:
I aquadag
II carbon black

The behaviour of secondary emitting surfaces in a radio valve

If it is desired to use a surface with very high or very low secondary emission in a radio valve, the coefficient of the secondary emission must remain constant during use. The electrodes of a radio valve are not only exposed to a bombardment by electrons, but are usually also gradually covered with barium atoms which evaporate from the hot oxide cathode.

Since metallic barium, as has appeared from the experiments discussed above, has a low coefficient of secondary emission, a surface with high secondary emission will in general be spoiled by being covered with barium atoms. It may therefore be necessary to avoid having barium atoms strike the secondary emitting surface.

It is also undesirable for a surface with only a slight secondary emission to be covered with barium. There is a possibility that a gradual oxidation will take place, and therefore that the coefficient of secondary emission will increase considerably. If we allow the oxide cathode of a radio valve whose anode is covered with carbon black to burn for 100 hours without applying an anode voltage, we obtain a variation in the secondary emission similar to that of curve *AB* in *fig. 11.* If an anode voltage of 100 volts is now applied, with an anode current of 40 mA, the factor δ falls again during the course of 100 hours to its original low value. The adsorbed barium atoms apparently disappear from the surface. This effect may be explained by a migration of barium atoms along the surfaces of particles of the carbon black toward greater depths of the carbon layer. The speed of this migration is much increased by an increase of temperature. When a carbon black surface of suitable structure is bombarded by electrons strong local increases of temperature occur which were estimated at about 300° C in the case in question.

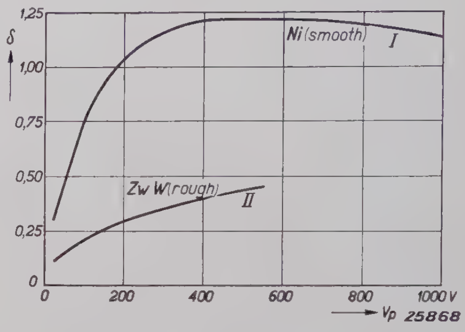

Fig. 10 Secondary emission of
I silver, deposited in a high vacuum
II silver deposted through 1 mm of argon

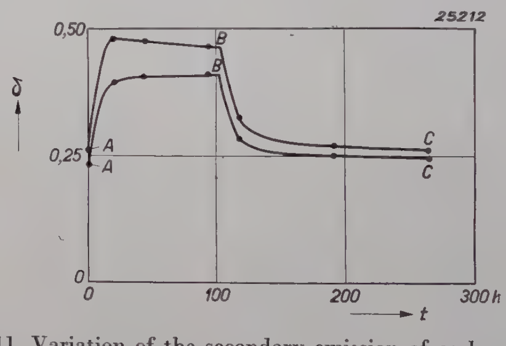

Fig. 11. Variation of the secondary emission of carbon black opposite an oxide cathode.

AB : $V_a = 0$; no electrons reach the anode; secondary emission rises with the time.

BC : $V_a = 100$ volts; electrons strike the anode; secondary emission falls to the original value.

AN ALTERNATING CURRENT DYNAMO WITH A FLAT CHARACTERISTIC FOR BICYCLE ILLUMINATION

H. A. G. HAZEU and M. KIEK.

621.313.322 : 629.118.3

A description is given of an alternating current dynamo in which the voltage at the terminals depends only slightly on the number of revolutions. This dynamo is intended for the feeding of a bicycle lamp, and is so constructed that when the bicycle is pushed at a walking speed it is adequately lighted, while at high speeds the lamp still has a satisfactory life.

Construction of the bicycle lamp dynamo type no. 7405

For the supply of a bicycle lamp alternating current dynamos are used not only of the type in which the permanent magnet is the stator and the winding the rotor, but also dynamos in which the winding is stationary and the permanent magnet rotates. The latter construction has been chosen for the Philips bicycle dynamo no. 7405, since, among its other advantages, no brushes are necessary, and therefore the possibility of poor contacts is excluded. For the generation of the necessary voltage at low speeds these dynamos must have a relatively large number of poles.

The field generated by the winding tends to demagnetize the steel magnet, and the demagnetization depends upon the load. In order to keep the resulting decrease in voltage as small as possible, we have used the special magnet steel "ticonal", whose magnetic induction at the working point is only slightly influenced by an alternating field. The so-called reversible permeability which determines this property is equal to only about 2. The induction B thus varies only slightly with the field strength H, and is not much greater in the metal than in air. The permanent magnet then need have no actual poles, but may simply be constructed in the form of a smooth, thin-walled cylinder magnetized to have eight poles.

As may be seen in the opened dynamo shown in *fig. 1*, the cylindrical magnet rotates within eight laminated pole shoes which run parallel to the axis and are joined above to form eight U-shaped magnetic circuits. Above the magnet a coil is wound about these projections in such a way (cf. *fig. 2*) that the energy fluxes through the projections which lie within the coil are opposite in direction to those through the projections which lie outside it.

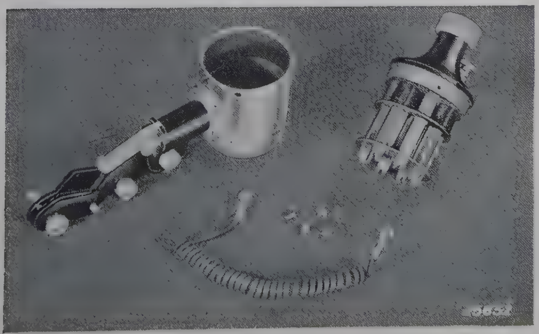

Fig. 1. Photograph of an opened bicycle dynamo type no. 6405.

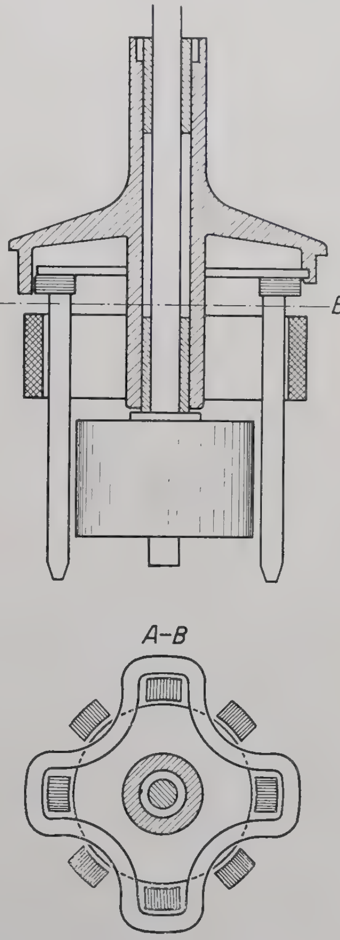

Fig. 2. Sketch of the construction of the bicycle dynamo. Above, a horizontal cross section, and below, a cross section through *AB*.

Method of obtaining a flat characteristic

In designing a dynamo suitable for a bicycle lamp it is desirable that it be so constructed that it is not only able to supply the necessary current of 0.5 to 1 A with the usual voltage of 4 to 6 volts at the normal speed of a bicycle of 13 to 15 km (8 or 9 miles) per hour, but that the lighting of the bicycle be adequate when it is pushed by hand at a speed of about 4 km ($2^1/_2$ miles) per hour. Moreover at a speed of 20 to 25 km (14 or 15 miles) per hour which for instance is the normal speed of tandems the voltage must not rise to such an extent as to cause the lamp to burn out.

If the leakage of the magnetic field, the losses and the field generated by the currents in the armature itself are neglected, the voltage of such an alternating current machine is directly proportional to the speed of its rotation, as is indicated in *fig. 3*, curve *a*. The light intensity of the lamp would then increase very rapidly with the speed of revolution, because a 1 percent increase in voltage on the lamp means about 3.5 per cent increase in the light intensity. However the requirement is made of the bicycle dynamo designer, that the construction of this alternating current dynamo be such that, upon being loaded with one or more bicycle lamps (for instance with both a front and a rear light as is now required by law in the Netherlands), a loss in voltage will occur, such that the voltage at the terminals depends upon the speed of rotation in the manner shown in curve *b*, fig. 3. In order to obtain such a relation the loss in voltage must increase more rapidly than the speed.

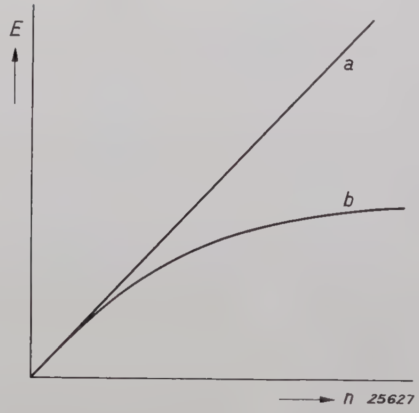

Fig. 3. Variation of the voltage at the terminals E of a dynamo with speed of rotation n. Curve a, non-loaded, and b, load of one or more lamps.

We shall prove in the following that a behaviour like that given in curve *b* is that of every dynamo, and we shall discuss the measures which may be taken to bring it about that the current becomes constant at as low a speed as possible.

If w be the number of turns of the winding, Φ the flux enlosed per turn, then the EMF generated

$$E = -w \frac{\mathrm{d}\,\Phi}{\mathrm{d}t}\,.$$

If we assume that the flux alternates sinusoidally as a result of passing the magnet poles, we may write:

$$E = -w\,j\,\omega\,\Phi, \quad \cdot \cdot \cdot \cdot \cdot \quad (1)$$

The flux Φ is generated partly by the permanent magnet and partly by the current I in the winding. This second part will be approximately proportional to the current, so that:

$$\Phi = \Phi_0 + C\,I \quad \cdot \cdot \cdot \cdot \cdot \quad (2)$$

It follows further from (1) that, when we introduce the total resistance R of the winding and the lamp:

$$I = \frac{E}{R} = -\frac{wj\omega}{R}\,\Phi \quad \cdot \cdot \cdot \cdot \quad (3)$$

By eliminating Φ from equations (2) and (3) we finally obtain:

$$I = \frac{-\,w\,j\,\omega\,\Phi_0}{R + w\,j\,\omega\,C},\ \text{therefore}\ |I| = \frac{w\,\omega\,\Phi_0}{\sqrt{R^2 + w^2\,\omega^2\,C^2}} \quad (4)$$

At a small speed of rotation the inductive resistance $w\,\omega\,C$ is still small with respect to R, and the current therefore increases proportionally to the speed. At a high speed, $w\,\omega\,C \gg R$ finally, and the current supplied becomes constant.

Equation (4) shows the essential point in the construction of a bicycle dynamo. The product $w\,\omega\,C$ must become large with respect to R for the lowest possible riding speed.

We shall consider the three factors of this product in detail.

The number of turns in the winding w

If there is a definite amount of space available for the windings of the coil, when w is increased, not only $w\,\omega\,C$ increases, but the internal resistance rises even more rapidly and R with it. Therefore an optimum number was found to be about 200; with this the dynamo has an internal resistance of about 4 ohms.

The frequency ω

The frequency ω is given by the product of the number of poles and the speed of rotation. A large number of poles is thus an advantage. In this respect the design of the dynamo in question is very advanced. A magnet with eight poles and having the small dimensions desirable in a bicycle dynamo could only be realized by using a magnet steel which, as a result of its low permeability at the working point, is only very slightly influenced by the demagnetizing field. Such a steel is the above-mentioned "Ticonal".

The constant C

The constant C indicates the flux through the coil which is generated by a current of 1 A. When the dynamo is constructed with no magnetic leakage, so that all the lines of force of the coil must go through the magnet, the flux is not very great because the magnet has a rather low permeability. For this reason the leakage is expressly made great by having the windings on projections of laminated iron which extend considerably beyond the winding and then run parallel to each other over quite a long distance and at a relatively small distance from each other (cf. figs. 1 and 2). The magnetic field of the winding can then be closed across these projections without the magnet being coupled.

Influence of eddy current

Since large losses of voltage must occur if the characteristic is to be flat, it might be thought that eddy currents would have a favourable influence on this factor. This is actually found to be the case; the loss of energy due to this cause is, however, not allowable in practice.

As previously explained in this periodical [1]), the eddy current losses may be represented by a resistance depending on the frequency, which is in parallel with the winding, and therefore also in parallel with the lamp. The loading resistance R is hereby reduced and the current will, according to equation (4), become larger and already reach a constant value at a lower frequency. In order to obtain a strong effect by this means, however, the parallel resistance due to the eddy currents must be small with respect to the external loading resistance. This results in the fact that the greater part of the energy is used to no purpose, and the dynamo drives too heavily. This may cause slipping.

This possibility of improving the shape of the characteristic therefore cannot be utilized. On the contrary, eddy currents must be avoided as much as possible. For this purpose the whole magnetic circuit is constructed of transformer stampings of less than $^1/_2$ mm thick.

Data of Bicycle Dynamo Type No. 7405

This dynamo has an internal resistance R_i of 4.1 ohms. At a speed of 14 km (9 m. p. h.) the normal voltage of 6 volts is delivered with 0.5 A, and at 38 km (24 m. p. h.) the voltage rises only to 7 volts. The no-load voltages are then however 24 and 57 volts respectively. In *fig. 4* the no-load characteristic is given (a) and the variation of the voltage at the terminals (b) as a function of the riding speed when loaded with an ordinary bicycle lamp taking $^1/_2$ A at 6 volts. We see from this that at a speed of 9 km (6 m. p. h.) the terminals voltage is still 5 volts, and that it decreases only to 4 volts at a speed of 6 km (6 m. p. h.), so that even at the lower speed the bicycle is adequately lighted. Further it may be seen from the no-load characteristic that the eddy current losses are relatively small. If there were no losses at all, the no-load characteristic would be straight (dotted), so that at 30 km (20 m. p. h.) the voltage would be 54 volts. This value is decreased by only 8 volts to 46 volts, due to the eddy currents, as may be seen from curve (a).

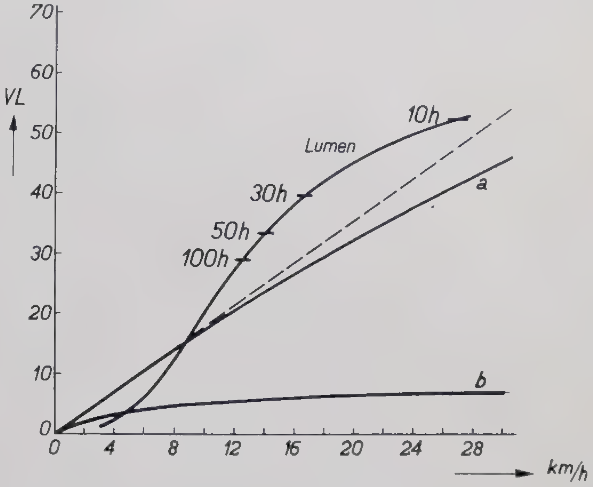

Fig. 4. Voltage in volts and light flux in lumens as functions of the riding speed. Curve a gives the variation of the no-load voltage and b the terminals voltage with the load of a lamp for 6 volts and 0.5 A. In the light flux curve the length of life of the lamp corresponding to the light flux also is indicated.

Moreover fig. 4 (c) also shows how the light flux in lumens varies with the speed, and the length of life of the lamp is also indicated for several values of the light flux. It may be seen that at the normal speed of 15 km per hour (10 miles) a light flux of 36 lumens is delivered and the lamp has a satisfactory life. At the very high speed of 27 km per hour (18 m. p. h.) the light flux increases only to 53 lumens, and the life of the lamp is 10 hours.

In *fig. 5* the so-called external characteristic of the dynamo is given, that is the terminal voltage R_k, the current I and the energy delivered W as a function of the external resistance R_u at a constant speed of 13.5 km per hour ($8^1/_2$ m. p. h.). From the short circuit current of 0.58 A at $E_k = 0$, the current I decreases with increasing R_u, and the voltage increases. The power delivered reaches a minimum between 20 and 30 ohms external resistance. For the sake of comparison an indication is also given (dot-dash line) of the way in which the power delivered W' varies when 140 turns of the same wire are used instead of 200, the number which was used in the final model. As was to be expected the maximum power for 140 turns occurs at a smaller external resistance.

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[1]) J. W. Köhler, Philips techn. Rev. **2**, 194, 1937.

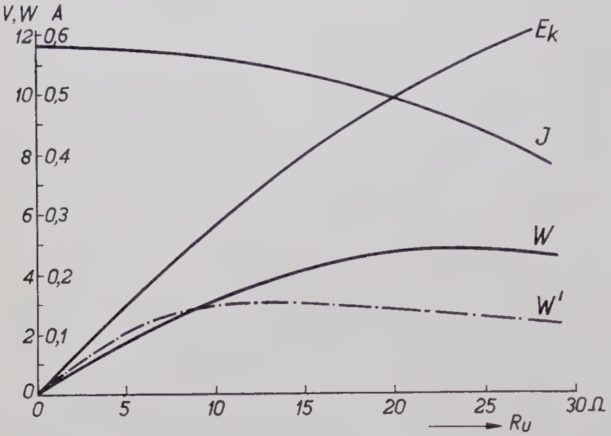

Fig. 5. Terminals voltage E_k, current I and power delivered W as dependent on the external resistance R_u; the so-called external characteristic of the dynamo. The power delivered W' is indicated by a dot-dash line for a dynamo provided with a winding of 140 turns, in contrast to the final construction with 200 turns.

If a lamp of 12 ohms for 6 volts and 0.5 A is used, the power delivered lies below the maximum, but a very flat characterisitic is then obtained, as is shown in fig. 4. When the dynamo is used care must be taken that the lamps in parallel with each other together take up a current at the terminal voltage supplied which is equal to the current indicated for the dynamo. If it is desired to use a lamp for 6 volts and 0.05 A for the rear light (required by law in the Netherlands), a head light for 6 volts and 0.45 A must be used when the dynamo is for 6 volts and 0.5 A.

Besides the original model for 6 volts and 3 W, dynamos constructed on the same principle for 8 volts and 4 W and for 10 volts and 4.5 W are now supplied. In *fig. 6* a bicycle dynamo type no. 7405 with accompanying head light is shown.

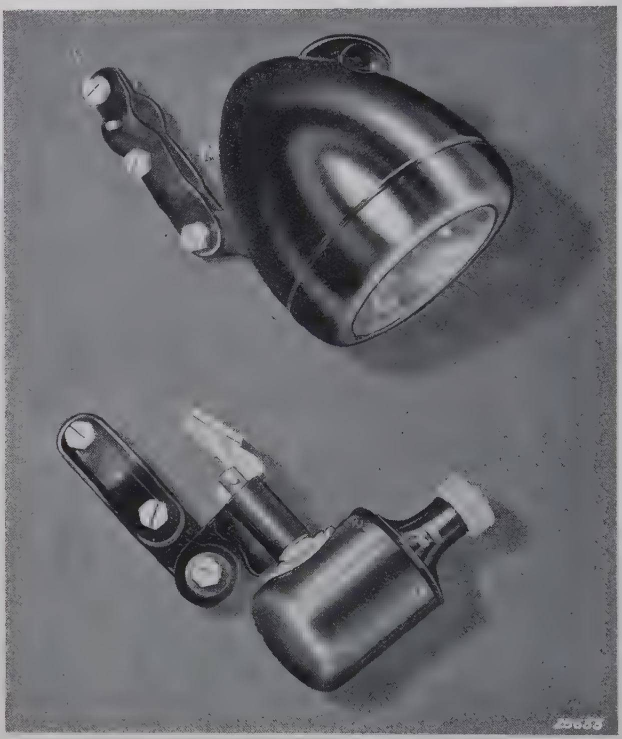

Fig. 6. Photograph of a bicycle dynamo type No. 7405 with the accompanying head lamp.

THE USE OF THE "PHILORA" HP MERCURY DISCHARGE LAMP IN AN ENLARGING APPARATUS

by J. A. M. VAN LIEMPT.

621.327.3 : 771.44 771.318.5

When a "Philora" HP mercury discharge lamp is used as the source of light in an enlarging apparatus, the exposure time can be considerably reduced, so that it is possible to work with silver chloride paper and with plenty of yellow light while adjusting and developing.

An ordinary electric lamp is usually used as a source of light in an enlarging apparatus. The power of this lamp must be limited to several hundred watts at the most because of the dimensions of the apparatus and with the heat development of the lamp.

Since when ordinary silver chloride contact paper is used the exposure times are relatively long, much use is now made of bromide paper, which is so much more sensitive that the exposure time can be shortened about 100 times. This is a great advantage especially in repetition work. The disadvantage of this paper, however, lies in the fact that it is somewhat more expensive and that in the dark room, the yellow light must be replaced by the weaker orange or light red light, under which it is more difficult to judge contrasts, especially in the darker parts of the picture. For these reasons experiments have been carried out by the court photographer P. Ziegler in The Hague, by the firm of Boomen in Amsterdam as well as by the writer of this article with the HP mercury discharge lamps which radiate relatively shorter wave lengths, and especially with the HP 300 lamp as a source of light. Normal contact printing paper was used. Since these lamps are supplied with the discharge tube placed at the geometrical axis of the lamp, the lamp must be placed perpendicularly to the axis of the tube of the enlarging apparatus. There would otherwise be a disturbing black spot in the middle of the positive as a result of the fact that the lamp radiates only a small amount of light in the direction of its axis.

It was found that the exposure time necessary to produce a good print can be about $^1/_{500}$ of that required by an ordinary electric lamp when the time is recalculated for the same energy, and about $^1/_{200}$ of that necessary with an ordinary electric lamp, recalculated for the same light flux. This means actually that when a mercury lamp of the type HP 300 (75 W) is used instead of an ordinary lamp of 200 W, and with normal silver choride contact printing paper, exposure times are just as short as those otherwise attained only with bromide paper. There is in addition the great advantage that one no longer need use light red light, but may again work with yellow light. As a source of yellow light, sodium light is highly to be recommended [1]). With this source it is possible to have a high intensity of light in the dark room for the making and developing of enlargements. The fact that the picture may be judged under normal intensities of illumination is very favourable to the result. With the much weaker red illumination it is impossible to distinguish the finer contrasts and the picture gives too hard an impression (and too dark in the shadow parts), so that one is always inclined to stop the development too soon.

The small heat development of the HP 300 mercury lamp, which is a favourable feature in any case, makes it possible in speed work, such as is often necessary in press photography, to enlarge the still wet negative, which has only been fixed but not washed, with less risk than when ordinary electric light is used where there is danger of the gelatine film becoming soft and blurring.

On point must still be noted. The cheaper enlarging apparatus has a lens which is only moderately achromatic. In many cases this will present no difficulties, but with special negatives such as those of line drawings and the like when printed on soft paper, there will be some difficulty.

When mercury light is used the possible achromatism of the lenses is somewhat more pronounced, because the composition of the light deviates from that of white light. It is therefore advisable to use a well corrected lens such as those supplied by reliable optical manufacturers.

If it is found that the lens already in use is unsatisfactory, improvement may be obtained by making the stop smaller. As a rule, for those special cases a decrease to *f*. 9 is enough. This of course is accompanied by some loss of light, but the exposure time remains so short that the advantage of the use of a mercury lamp is still very considerable.

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[1]) For the value of the "Philora" sodium lamp in photography see Philips techn. Rev. **2**, 24, 1937.

THE EXAMINATION OF THE MACRO-STRUCTURE OF MATERIALS AND PRODUCTS WITH THE HELP OF X-RAYS. IV

by J. E. DE GRAAF.

539.26534.844

In a purely mechanical manufacturing process the differences between the products produced will in general be slight. It is usually sufficient to examine samples only, since an irregularity in the manufacturing process seldom occurs.

As soon, however, as the changeable human being begins to take an important part in the manufacture of the product, every article must in principle be checked, at least when high quality is important. This subsequent control is naturally somewhat unsatisfactory, so that attempts are made by means of work tests to determine the "value" of the worker. In such tests maximum performance only is usually determined, since the worker approaches such a test quite differently than he approaches his routine work; and in any case great deviations from the test "value" may be expected as a result of psychological and physical influences and the like. In precise work considerable differences have more than once been found between work done at night and that done in the daytime, or between articles made on Monday and those made on Tuesday. By continually controlling production with the help of X-rays it is possible both to detect too dangerous mistakes promptly, and to take measures toward removing the causes of mistakes (by improving the illumination for instance). The very presence of such a control often has a strong preventive influence, which is manifested not only in better work, but also in better care of implements and tools.

One of the operations to which the above specially applies is electric welding. Mistakes often occur through nonchalance or ignorance, which mistakes are different for every welder. These mistakes must then be analyzed in order to be able continually to point out to the welder his own particular failings.

The diagnosis of mistakes in electric welding [1])

In the first place a distinction can be made between mistakes in the welding process and mistakes in the preparation of the weld. Among the latter, for example, belong an incorrect form of electrode and dirty plates.

In the second place a distinction can be made between, I, gas enclosures (circular dark spots with sharp out-lines and heavy blackening), II, slag enclosures (usually vague irregular limits) and III, flaws of a linear form such as cracks and imperfect joints (contrast closely dependent on the direction of the rays [2])). Several examples of these defects in butt welding are given below together with an account of some of their causes.

With other welding rods than the used PH-50 (cf. Philips techn. Rev. 2, 135, 1937) the illustrated faults only show unimportant changes.

A. Mistakes in the welding operations

Group I: Gas enclosures.

Fig. 1. Gas enclosures.

Characteristics: circular dark spots often in groups with relatively sharp outlines and heavy blackening; their diameter is seldom more than 2 mm.

Causes: too long an arc (too little protection from air); too heavy current (especially where the welding has been done with the last short end of the welding electrode, which often stands red-hot).

Group IIa: Slag enclosures entirely within the molten metal.

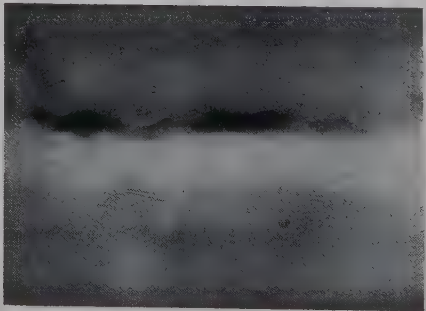

Fig. 2. Running out [2]) of the slag on a flat plate.

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[1]) As in the precading articles (Philips techn. Rev. 2, 315, 350 and 377, 1937). The x-ray photographs are reproduced in original size.

[2]) Cf. Philips techn. Rev. 2, 351 (1937).

[3]) Under the term "running out" is meant the fact that the liquid flux (cf. fig. 16 of the article by J. Sack onWel-

Characteristics: a heavy line, sometimes several mm wide with irregular curved outlines and moderate to heavy blackening.

Causes: incorrect waving motion; the electrode passes over the already molten slag and the drops of iron fall to both sides of a slag channel.

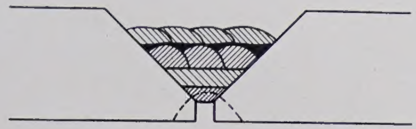

Fig. 3. Diagramatic representation of slag enclosures in the V shaped weld groove. Footnote [4]) fig. 12 explains the signifacation of the dotted line.

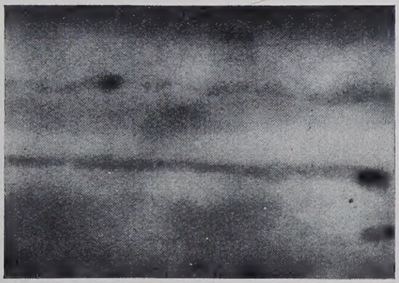

Fig. 4. Running out of the slag in the grooves between the convex surface of the first layer of metal deposited (cf. fig. 3).

Characteristics: narrow, vague, oscillating lines, often of moderate blackness; interruptions often occur (sometimes with the ends bent outward).

Causes: due to too weak current or too limited waving motions the surfaces of the underlying layer have become too convex and grooves are therefore formed between them. (Other narrow grooves, such as those at the bottom of a V-joint may lead in this way to slag enclosures which have their own special characteristics).

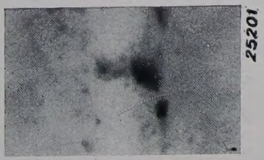

Fig. 5. Crater enclosure.

Characteristics: a half-moon shaped spot with the width of the weld, low degree of blackening and sharpness; often accompanied by gas bubbles.

Causes: after an interruption of the arc, welding is recommenced at or before the old crater, instead of beyond it; slag runs into the hollow of the crater when another layer is applied on top of it.

Group IIb: Slag enclosures between deposited metal and base metal.

As soon as there is any suspicion of the presence of this kind of defect, X-ray photographs must be taken with the rays incident along the original boundary of the base metal, for instance along the wall of the welding groove. This type of defect may result in dangerous cracklike faults (imperfect joining).

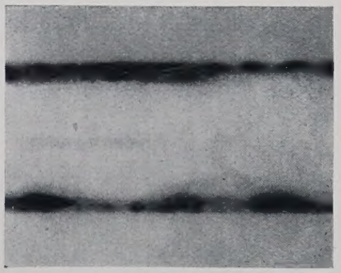

Fig. 6. The supply of heat to the groove is continually too low.

Characteristics: often a fairly broad line with a straight sharp boundary at the wall of the groove, extending over long distances.

Causes: the welding electrode was not directed sufficiently into the angle between the weld and the wall of the groove, so that the slag in that angle was able to solidify. This is often due to the postion of the welder, when it is such that he is unable to see into the angle.

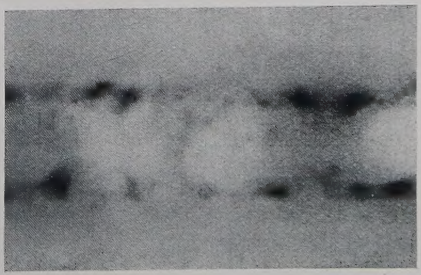

Fig. 7. The supply of heat is very irregular and often insufficient.

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ding and Welding Rods in Philips techn. Rev. **2**, 129, May 1937) does not cover the material deposited (the weld) but runs out over the cold surface of the work ahead of the weld.

Characteristics: enclosures limited by a straight line along the wall of the groove and having very irregular shapes and many interruptions.

Causes: too long an arc, which in the waving motion jumps over too quickly to the wall of the groove and heats the angle between the weld and the wall irregularly.

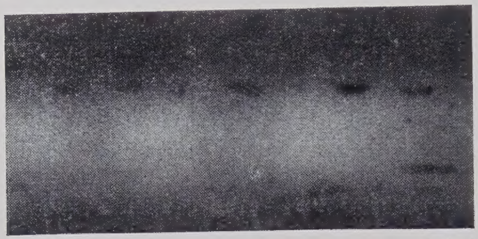

Fig. 8. Triangular enclosures.

Characteristics: triangular enclosures bounded by a straight line along the wall of the groove and sharply outlined, at fairly regular intervals (alternately along both walls of the groove).

Causes: due to too rapid advance of the weld, a zigzag layer was formed; between the wall of the groove and the angles or curves of the weld, slag is enclosed during the welding of the following layer.

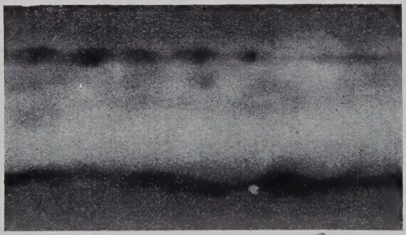

Fig. 9. Undermining.

Characteristics: enclosures lying outside the original limits of the weld, and having a wavy outer boundary and a vague irregular inner boundary; usually accompanied by the fault of fig. 6.

Causes: too long an arc (as in fig. 6) which melts too much metal from the wall of the groove; in depositing the following layer, the undermined spot is usually filled with slag instead of with metal.

Group IIIa: Imperfect joints.

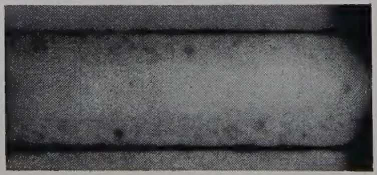

Fig. 10. Imperfect joints.

Characteristics: straight lines, usually fine and without side branches lie along the walls of the groove. They are almost always accompanied by slag enclosures.

Causes: The electrode metal is not fused together with the base metal because of inadequate supply of heat to the latter (for instance because the arc was not sufficiently directed upon the wall of the groove just as in the case of the defect in one layer only in fig. 5; in fig. 9 the defect lies higher up on the wall than in fig. 5).

Group IIIb: Cracks.

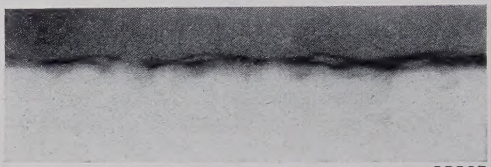

Fig. 11. Cracks.

Characteristics: fine, often branched lines; they are usually smooth in the base metal, while in the metal deposited or along the wall of the groove they are usually irregular; these defects are often difficult to discover.

Causes: because of immoderate or irregular shrinking the stresses occurring are too great to be relieved sufficiently by flowing of the metal.

B. Faults in the preparation

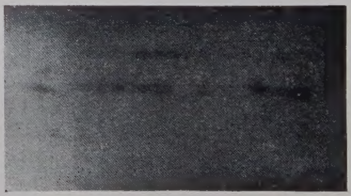

Fig. 12. Faulty cutting out of the groove for a counter weld [4]).

Characteristics: a line close to the outer surface of the counter weld, somewhat irregular and often broken, with vague boundaries and slight blackening.

Causes: the cutting out of the root was done with a chisel which made too sharp a groove. The slag ran out in this groove as in fig. 3.

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[4]) After the V-shaped weld groove has been welded full, in the case of thick plates the portion indicated by a dotted line in fig. 3a (the "root") is cut out, since this portion is often filled with slag and badly deposited metal.

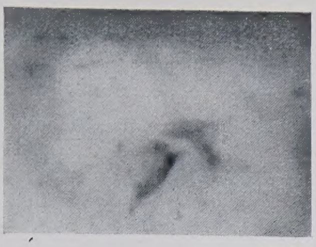

Fig. 13. Faults in the filling of too narrow holes.

Characteristics: on a stereo-photograph which gives a special impression of the enclosures, the slag was found to be enclosed in the form of a spiral.

Causes: in the too narrow hole the slag could not be sufficiently well removed during the filling of the hole with molten metal with a spiral motion.

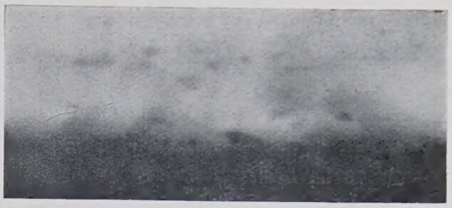

Fig. 14. Fault in the method of filling the seam.

Characteristics: at regular distances in the seam occur collections of vague linear or pointed enclosures of slight darkening.

Causes: a section of the seam about 30 cm in length was completely filled, then a following section, etc. The rough end of one finished section was not cut out smoothly before the beginning of the next.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

1251: J. van Niekerk and F. Franken: On the influence on chicks of very large amounts of antirachitic vitamine of animal origin (Landbouwk. T. **49**, 742 - 748, Oct. 1937).

The influence of the administration of large quantities of vitamine D on the growth and death of chicks is studied. The limitation of growth and the death rate are found to be proportional to the degree of the excessive concentrations of vitamine D.

These results are only observed with high overdosage of the vitamine. In connection with the small concentration in which vitamine D appears on the market, possible mistakes need cause no anxiety as to a poisoning effect. If the administration of vitamine D to chicks which have had too much is stopped, they continue to grow normally. Finally methods are given for the quantitative determination of the poisonous effect of antirachitic preparations with chicks as test animals.

1252*: R. Houwink: Die Viskosität in konzentrierter Lösung (Oesterr. Chem. Z. **40**, 472 - 475, Nov. 1937).

The behaviour of concentrated solutions, which is of such fundamental significance in colloid chemistry problems and in the treatment of the subject of highly polymerized materials is discussed in this article (Cf. **1199**).

1253: M. J. O. Strutt und A. van der Ziel: Die Ursachen für die Zunahme der Admittanzen moderner Hochfrequenz-Versterkerröhren im Kurzwellengebiet (El. Nachr. Techn. **14**, 281 - 293, Sept. 1937).

From measurements carried out on high-frequency amplifier valves, input losses, output losses and reaction admittance are found to increase considerably with the frequency for short waves. In contrast to the usual conception that the cause of this must always be sought in the transition times of the electrons, it follows from many measurements that $^1/_2$ to $^1/_3$ of the input losses and practically all of the output losses and reaction admittance must be ascribed to induction effects inside and outside the modern high-frequency amplifier valve of normal type (AF 3 and AF 7 for instance). A general theory about the influence of induction effects on the admittances is proposed for different types of valves. The formulae found agree with the measurements, which is not the case with the formulae for the influence of the transition times of the electrons on the admittances of the amplifier tubes.

1254: E. M. H. Lips: The construction of castings with relation to the "stress-free" requirement (Metallbewerkung, 4, 289 - 291 and 309 - 312, Oct. 1937).

Non-uniform cooling of a casting causes casting stresses. A description is given of what is meant by non-uniform cooling, and in what way uniform cooling, and thus absence of stresses in the casting, can be promoted by giving suitable dimensions to the casting. The experiments were carried out in collaboration with the iron and metal foundry "De Globe" in Tegelen.

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*) An adequate number of reprints for the purpose of distribution is not available of those publications marked with an asterisk. Reprints of other publications may be obtained on application to the Natuurkundig Laboratorium, N.V. Philips' Gloeilampenfabrieken, Eindhoven (Holland), Kastanjelaan.

1255: W. Elenbaas: Über eine Kombination der hydrodynamischen Theorie des Wärmeübergangs und der Langmuirschen Theorie (Physica 4, 761 - 765, Oct. 1937).

Langmuir's theory of the transfer of heat by wires of various diameters to gases at various pressures is combined with the hydrodynamic theory, especially that of Nusselt.

Langmuir's theoretical curve, with a suitable choice of parameters, agrees with the experimental curve of Nusselt. By combination of the two theories the transfer of heat in all diatomic gases can be calculated with the help of a single constant.

1256: J. A. M. van Liempt and J. A. de Vriend: Testing focal plane shutters (Physica 4, 811 - 827, Oct. 1937).

A description is given of the method by which a focal plane shutter can be thoroughly tested with the help of a cathode ray tube with respect to shutter time, width of the slit, motion of each of the blinds, time of exposure and efficiency.

1257: J. L. Snoek: Volume magnetostriction of iron and nickel (Physica 4, 853 - 862, Oct. 1937).

The volume magnetostriction is measured by means of an aluminium dilatometer, in which the thermal expansion of the test rod and of the filling liquid due to the magnetocaloric effect are compensated by the expansion of the dilatometer. This is only exactly the case at a definite temperature, but corrections can be applied for other temperatures.

At room temperature accurate measurements have been carried out on pure iron and nickel. As was to be expected, the slope of the line which represents the specific elongation as a function of the magnetic field is scarcely influenced by the state of internal stress of the test rod. There is, however, considerable parallel displacement. The change in the effect with temperature is not greater than the experimental errors.

1258: C. J. Bakker: On the efficiency of the production of artificial radio-active substances by slow neutrons (Physica 4, 863 - 870, Oct. 1937).

Solutions of various salts were irradiated with neutrons from a radium-beryllium preparation in order to produce artificial radioactive elements. The efficiency in the production of radio-chlorine with a half life of 35 min was 1%, radio-bromine, half life 18 min: 16%, radio-bromine, 4 hours: 7%, radio-bromine, 36 hours: 0.6%, radio-iodine, 35 min: 3% and radio-manganese, 2.5 hours: 6%. Minimum values were determined for the capture cross section for slow neutrons.

1259: E. M. H. Lips: Härtemessungen an Gefügebestandteilen (Z. Metallk. **29**, 339 - 340, Oct. 1937!.

The measurement of the hardness of structural components is described (of Philips techn. Rev. **2**, 179, 1937).

1260*: C. J. Dippel: Reversible and irreversible phenomena in the adsorption of vapours on salt surfaces deposited by sublimation (Chem. Wbl. **34**, 676 - 678, Oct. 1937).

The molecular relation in the adsorption of caesium and iodine on sublimed calcium fluoride is not constant. This may be explained, in connection with other investigations, by means of the assumption that this relation is actually the product of a pure adsorption relation and a relation of the areas of the surface.

Under the influence of the adsorption of caesium the available portion of a calcium fluoride surface may become greater (opening of space between lamellae) due to a kind of swelling. This is partially reversible and partially irreversible, since a portion of the substance adsorbed in held by irreversible bonds. This hypothesis also offers an unforced explanation of the adsorption hysteresis found in the adsorption of iodine.

1261: A. E. van Arkel and J. H. de Boer: Supplement to "Chemische Binding" (31 pages; Centen, A'dam 1937).

In this supplement to the book „Chemische Binding als electrostatisch verschijnsel" published in 1929, the authors have summarized some of the most important points regarding which theories have been developing rapidly in recent years. Among other features, the formation of complexes and the phenomenon of condensation under the influence of van der Waals' forces are discussed.

1262: M. J. O. Strutt: Measures des constantes caractéristiques de quelques penthodes haute-fréquence pour des fréquences de 1,5 à 300 mégacycles par seconde (Onde él. **16**, 553 - 577, Oct. 1937).

This article is a French version of **1243**.